ABOUT THIS BOOK

Has atomic energy really any peaceful uses? Where is uranium found? What does a Pile look like? What are the risks to health from the radiation given out by decomposing atomic nuclei – and how are they avoided? The answers to these and many other questions are outlined by a group of British and American scientists in a series of chapters which describe briefly the nature of the atom and the history of its study, how the materials for atom bombs are made and what happens when a bomb is exploded, how radio-isotopes are to-day being used in industry and medicine, how they are produced in nuclear reactors, what the future is for this new source of power, and many other topics. This is a simple introduction to the scientific background, completely non-political, but likely to be useful to all who wish to understand some of the problems of the day, who have a part in military or civil defence, or who are entering this new industry growing up round uranium. Sixteen pages of illustrations show part of the plants of four of the five countries now actively engaged in atomic energy development (unfortunately no picture is available of Russian work), the Harwell pile being shown in more detail, some of the health precautions are visible, uranium mining in Canada is illustrated, and so on. This section forms a story on its own.

This is a revised and enlarged edition
of Science News 2.

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ATOMIC ENERGY

A. Correia-Afonso
21/6/1950

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A. Correia-Afonso
21/6/1950

Atomic Energy

EDITED BY

J. L. CRAMMER

AND

R. E. PEIERLS, C.B.E., F.R.S.

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SCIENCE NEWS 2

(February 1947)

'Nuclear Reactors' by Sir John Cockcroft is taken from a lecture delivered to the Metropolitan Vickers Electrical Company Apprentices Association, I.C.I. Ardeer Chemical Club, and the Mathematics and Physical Society of the Royal College of Science.

'Raw Materials for Atomic Power' by Professor Tilley is reproduced from *Atomic Energy: Its International Implications*, a Discussion by a Chatham House Study Group (published January 1948), by arrangement with the Royal Institute of International Affairs.

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Editorial Note

THIS book in original intention was to be little more than a re-issue of *Science News* 2, which has long been out of print. We took the opportunity, however, not merely to bring all the articles up to date, but to fill certain gaps in the original edition, with the result that four of the present nine articles are completely new, and so are most of the illustrations. The changes represent the swing of interest from atomic bombs to the peaceful uses of nuclear energy, and reflect the development of the British Atomic Energy Research Establishment at Harwell. We are fortunate in being able to include articles by the Director (Sir John Cockcroft) and by two of his staff which cover the industrial possibilities of nuclear power, the scientific uses of neutrons, and the industrial and biological uses of radio-isotopes. In addition we have added short articles on the distribution of uranium ores throughout the world, and on the dangers of radiation to health.

It is our hope that this book may prove as useful as its predecessor as a simple yet comprehensive introduction to the whole subject. It is elementary enough to be read without previous knowledge by the interested layman, and should prove useful as a beginning to anybody meeting some aspect of Atomic Energy in his work, whether it be public health, civil defence, academic science, or industry.

J. L. C.
R. E. P.

1

The Release of Atomic Energy

R. E. PEIERLS, C.B.E., F.R.S.

1. *Introduction*

The explosion of atomic bombs, in the trial at Alamogordo, New Mexico, and in earnest over Japan, marked the end of a continuous development that started with the discovery of radioactivity by Becquerel in 1896. Throughout this time the problem held the attention of scientists as one of the most fascinating fields of discovery; but they were more fascinated by what they could learn in this field about the laws of nature than by the prospects of practical applications. It is true that, probably from the very beginning, physicists were aware of the large sources of energy stored in all materials and they all liked to speculate what it would mean if these sources could be tapped, but any practical realisation seemed remote.

In spite of the enormous progress made up to, say, 1938, which was laying the foundations for future development, the situation was then still the same. The study of the atomic core or 'nucleus' was by then a well-established and important branch of physics; the splitting of the atom had not only been studied, but could be produced at will in many university laboratories; but there was as yet no indication that it might have practical significance outside such laboratories.

But, by 1940 we find research teams independently in many countries attacking the problem of tapping these new sources of energy, as a terribly practical project, with the hope of success in a short time.

What had happened in the interval was the discovery of the 'fission' of uranium by Hahn's experiments and their interpretation by Meitner and Frisch, and the proof, given shortly after, by Joliot, Halban and Kowarski in Paris and by Fermi and Szilard and their collaborators in America, that in this fission several secondary neutrons are given off.

To the layman these discoveries would have appeared as inconspicuous notes in scientific periodicals stating some numbers obtained in laboratory experiments, yet to any physicist who had ever speculated on the release of atomic energy, these results meant that such speculations were suddenly removed from fantasy to actual possibility.

To be sure, much had to be done, and much had to be learnt, before success was certain, but this moment may be regarded as the turning-point. In the present article we want to explain the arguments that made these discoveries so sensational, and also to outline the work that had to be done from there, which will be covered more fully in the following chapters of this book.

2. *State of Knowledge before Discovery of Fission*

Later articles will also tell the story of atoms and their structure, but we need a few facts here for our first survey. Atoms are the units of which matter is built. They are extremely small, even the heaviest ones, like uranium atoms, weighing only as much in comparison with a melon as the melon in comparison with the earth. Even though atoms are too small to be visible in the most powerful microscopes, the last sixty years or so have brought many methods of proving their existence, and the article by Frisch will describe examples of ways in which the trace of a single atom can be detected.

It was found that each atom has a central core, or 'nucleus', which carries a positive electric charge. This is surrounded by electrons, which are very light particles of a weight about 2000 times smaller than the lightest atom; each electron carries a negative charge.

All ordinary chemical changes in matter are concerned only with the arrangement and movement of the electrons, and usually, in heavy elements, only the outermost electrons, which move with lower speeds and are easier to influence than the inner ones.

The nucleus of the atom comes in only in so far as the amount of electric charge it carries determines the number of electrons necessary to neutralise it; the number of electrons determines the chemical nature of the atom. But in all ordinary chemical or mechanical changes the nucleus of the atom does not change its condition.

This is not surprising because the forces that hold the constituents of the nucleus together are immensely stronger than those that govern the motion of the electrons surrounding it. For example, the energy required to break up the nucleus of a helium atom is about a million times that needed to prise an electron loose from the helium atom.

Accordingly, while energies involved in atomic processes are usually measured in electron volts, those in nuclei can be expressed in million electron volts. An electron volt is the energy which an electron acquires in passing through an electric field under the influence of a potential difference of one volt. Taken absolutely, it is a very small amount of energy, since the charge on an electron is a very small fraction of the electric charges that we are accustomed to deal with. On the other hand, burning a substance such as coal releases about four electron volts *per atom*, and then the energy contained in every quarter pound equals about one kilowatt-hour, the familiar unit of electric power.

It was always evident that if one could succeed in producing a reaction between atomic nuclei one would deal with very much larger amounts of energy.

That some atomic nuclei were capable of undergoing changes which released energy was known ever since the work of Rutherford and others had led to an understanding of radioactivity. Radioactive elements, i.e., elements that, like radium, continuously emit penetrating radiations, were shown to have nuclei which are unstable and tend to break up, expelling, when they do so, particles of high energy. The particles emitted by such radioactive nuclei are usually positively charged, and they carry away some of the charge on the nucleus, so that the nucleus remains with a smaller charge; the remaining atom retains fewer electrons and is therefore an atom of a chemically different substance.

Hence the process of splitting atoms, and of transmutation of one substance into another, is not new, but has been going on in nature ever since there was radium, uranium, or any other radioactive element. But there is no way of controlling, of accelerating or stopping this process. It goes on at its own pace, and of any quantity of radium, for example, one part in about 580,000 will break up every day, so that after 1600 years only half the original amount is left. If we could hurry nature and make all the radium break up in a few minutes, even small quantities of radium would constitute a respectable source of energy.

Rutherford himself showed later (1919) that the splitting or 'disintegration' of nuclei could be produced at will – at a price.

For this purpose Rutherford used as projectiles the particles emitted by radium, or other radioactive elements, which he had called 'alpha-particles', and which turned out to be nuclei of helium, i.e., helium atoms stripped of their electrons, and hence positively charged. These particles are thrown out by the radioactive substance at high speed, the energy carried by each particle being of the order of several Mev (million electron volts). In passing through light elements they would occasionally collide with one of the nuclei, and combine with it, causing the ejection of some other particle, usually a 'proton', i.e. a hydrogen nucleus.

Thus the artificial transmutation of elements had been achieved, but the amounts were minute and the energy released quite negligibly small. One must here remember that the atom represents a target with an extremely small bull's eye, since the nucleus has an area which is ten million times smaller than that of the rest of the atom. Hence, since one cannot aim the projectiles, only a minute fraction of the shots will, in fact, be hits. Each alpha-particle will, in passing through matter, go through many atoms in turn, and thus have many tries at hitting a nucleus. The number of such tries is, however, limited, since during this passage the particle continuously collides with electrons, thereby gradually losing speed. Now, as its speed is reduced, it finds it increasingly difficult to reach a nucleus, since both the particle and the nucleus are positively charged and like charges repel each other. While a fast particle can overcome this repulsive force fairly easily, this is almost impossible for a slow one, and below a certain speed the particle is practically incapable of reaching the nucleus.

Hence most of the particles must get slowed down and finally stopped without ever making a hit, and only a small fraction, sometimes one in 100,000, sometimes one in a million, are successful. This means that the number of atoms we have split must be at least 100,000 times smaller than the number of radium atoms that broke up to give the alpha-particles we used. Therefore, any energy we may be able to recover from the particles which we have knocked off the nuclei we have succeeded in hitting, is many thousand times smaller than that of the alpha-particles we have used, so this method is certainly no way of releasing energy for practical purposes.

From our present point of view the situation was not materially affected by the discovery of Cockcroft and Walton, who showed that instead of the alpha-particles one could use hydrogen or other nuclei accelerated artificially in an evacuated tube with a voltage of the order of a million volts applied to its end. This made the job easier and speeded up research, but still most of the projectiles stopped before finding a target, and the energy wasted was incomparably greater than that generated.

An important step was, however, the discovery of the neutron by Chadwick in 1932. The neutron is a heavy particle of practically the same weight as a proton, or hydrogen nucleus, but it differs from it by carrying no electric charge. This means that in passage through matter it has no effect on the electrons in its way, and hence it is much harder to detect than charged particles, which are mostly observed by the violent disturbances they cause in atoms along their way. Neutrons do, however, interact strongly with nuclei at close range; they have a strong tendency to attach themselves to nuclei. In fact all nuclei are built of neutrons and protons.

This means that neutrons are much more effective projectiles than charged particles for splitting nuclei, since they are not slowed down in their passage through matter except when they have direct hits on nuclei; moreover, even a slow neutron has a good chance of a direct hit, since it is not kept away from the nucleus by an electric repulsion.

If, therefore, we use neutrons as projectiles, we may hope that in suitable conditions a fair fraction may break up nuclei, instead of only every millionth or so, as with charged particles.

But how are we going to produce neutrons for this purpose? The easiest way to produce neutrons is to bombard a very light element such as beryllium, for example, with alpha-particles from radium. The neutrons from this process were the ones first discovered. We can see that this only moves the difficulty one step further along, since we know already that hitting nuclei with charged particles is necessarily a very wasteful process. While a neutron has a fair chance of making a hit, we can obtain it only by a process in which we use up much more energy than we can expect to recover from the hit of a neutron on a nucleus.

3. *Discovery of Fission and its Significance*

This was the state of affairs when fission was discovered. Hahn and his collaborators bombarded uranium with neutrons, in the expectation that neutrons might get lodged

in uranium nuclei, thus building up a still heavier nucleus. This might be expected to increase its electric charge by the process known as 'beta-transformation' and thus form new elements beyond the end of the series of elements then known, of which uranium, carrying a charge of 92 units on its nucleus, was the last. We now know that this formation of 'transuranic' elements does indeed take place, but in searching for it, Hahn found a completely new phenomenon.

As usual, the amount of new material that is made by such a bombardment is too small to be seen or weighed or handled in any other conventional way. However, such new elements are often radioactive, since, having changed their weight by the capture of a neutron they tend to change their charge also, and this is achieved by a beta-transformation, in which the nucleus gives off an electron (which for our purpose is essentially a charge without weight). Now these fast electrons or beta rays can be detected by sensitive counters and other methods described in Frisch's article and therefore we can detect such substances in very small amounts. Their chemical nature can be studied by performing a chemical analysis of the sample that had been exposed to the neutrons and seeing which fraction gives the beta rays. For example, if this sample is subject to a chemical process in which barium would precipitate, while other elements remained in solution, we would see whether the solution or the precipitate was an emitter of beta rays. In the latter case we would say that the radioactive element which we had produced had the chemical properties of barium.

This was indeed found by Hahn, to his surprise, since none of the atoms heavier than uranium should have these chemical properties. More careful analysis showed that there were a great number of radioactive substances present with chemical properties similar to many elements of roughly half the atomic weight of uranium.

Lise Meitner and O. R. Frisch then pointed out that this must mean that the neutron had caused the uranium nucleus to undergo fission, or in other words to split into two roughly equal parts. It was known already that the heaviest nuclei were of an uneconomical size. They were so highly charged that the electric repulsion of like charges tended to break them up in spite of the binding forces cementing them together. It was known that the energy contained in a uranium nucleus was much more than twice that of a nucleus of half the weight and half the charge. In the ordinary way, such a nucleus holds together since a strong force opposes any effort to break it up. If some work is done to overcome this force (like the effort required to pull the plug out of a full bath-tub against the water-pressure), the further breaking up of the nucleus proceeds by itself and in doing so much more energy is liberated than had to be invested at first.

It was soon verified by many physicists in many places that this explanation was right, since they actually found very heavy particles moving at high speeds, which were, of course, the fragments of uranium nuclei, thrown apart violently as the nuclei split. They carry most of the energy liberated in the process, and this was found to be about 160 million electron volts. To appreciate the significance of this figure, we remember that the energy liberated in burning one atom of coal is 4 electron volts, whereas in most radioactive processes each atom contributes an amount of the order of a few million electron volts. Here was, then, a much more powerful process than any other known.

Soon after this Joliot, Halban and Kowarski in Paris and two groups in America including Fermi and Szilard showed that in addition to the fission fragments, some neutrons were the result of the process, and that for each uranium nucleus split, several neutrons were obtained. This was the crucial fact, for here was a source of neutrons for which one did not have to waste millions of charged particles in an effort to hit some nuclei.

Supposing, for simplicity, that *all* neutrons hitting uranium nuclei cause fission, and that there are two neutrons given off for each fission. Then if once we have caused one uranium nucleus in a large mass of pure uranium to split, we have two neutrons. Both of these will continue on their path until each hits another uranium nucleus and the splitting of those two nuclei will produce four neutrons altogether. In the next 'generation' we shall have eight neutrons, and clearly in this way the number will grow extremely rapidly; after twenty generations we shall have produced about a million neutrons, and only eighty generations are required to create in this way as many neutrons as there are atoms in a sizable piece of uranium metal. Hence, if the process could really be allowed to continue in this way, a staggering amount of energy would have been released in a very short time, since the whole process of using up these eighty generations would take only about eighty times the time that a single neutron needs to find its next victim amongst the uranium atoms.

In this process, which is usually described as a 'chain reaction', lies the key to the release of atomic power on a large scale, and from the description it is clear that the two essential features are a reaction which can be caused by a neutron and releases energy, and the emission of secondary neutrons from this reaction.

The picture given here is, of course, over-simplified. It is not essential that we should assume just two neutrons to be emitted in the reaction; we would equally well get the chain reaction if this number were greater or less than two, provided there was more than one neutron for every neutron used up, so that, as the chain proceeds, the total number of neutrons will grow. It is, however, very important that in reality not every neutron generated in this way will again lead to the splitting of another uranium nucleus.

There are two reasons for this. The first is that sometimes when a neutron hits a uranium nucleus it may get lodged in the nucleus, thus forming one of the trans-uranic elements for which Hahn was looking, and these neutrons are evidently lost from the process since they do not directly produce any offspring. Similarly, any other elements present as impurities in the uranium or as necessary materials of construction may absorb neutrons and thereby reduce the number of secondary neutrons that, on the average, each primary neutron will produce. The second reason is that in practice one always deals with a finite amount of uranium and that the leakage of neutrons from the surface may be appreciable. It has here to be remembered that the 'mean free path', i.e., the distance that a neutron can run in uranium, on the average, without hitting any nucleus is quite appreciable. Unless the dimensions of the uranium are rather greater than this mean free path, each neutron will have a fair chance of running out of the material before it could hit a nucleus and produce fission.

We can still use the picture of a chain reaction, only we must not count as significant the number of secondary neutrons produced by the splitting of one uranium atom. Instead we must state what fraction of these will *not* escape through the surface or be absorbed without splitting uranium nuclei, since only these amongst the offspring of any particular neutron can cause further splitting and thus continue the chain. This number, usually called the 'multiplication factor' (or sometimes 'reproduction factor'), and denoted by k, is then vital for the possibility of the chain reaction. If the number is less than one, say if it is 0.99, no chain reaction will form. If, in some way, we have produced 100 neutrons in such a system, the next generation would contain only $100 \times 0.99 = 99$. The next after that 99×0.99, which is about 98, etc. On the other hand, if, for example, $k = 1.01$, we would from an initial 100 have 101, 102, etc., and after every seventy generations the neutron number would double.

Further investigation of these problems brought the following facts to light. In ordinary uranium the chance of any given neutron causing fission is very small: most of the neutrons will actually be caught and retained by the nucleus. The average distance which a neutron has to travel in ordinary uranium before causing fission, even if it is not absorbed on the way, is very large, and, therefore, even if absorption did not outweigh production, very large quantities of uranium would be necessary to produce a chain reaction.

4. *Chain Reaction with Slow Neutrons*

An obvious remedy for this last difficulty appeared at once to be the use of very slow neutrons, since it was known that, as in many other cases of collisions with nuclei, both the capture and the fission of uranium happen much more easily at very small velocities. (It might be said with some oversimplification that a fast neutron does not stay near the nucleus long enough to make the latter realise its presence.) It was known that one could easily slow down neutrons if one allowed them to travel through a medium containing very light elements. For example, very suitable slowing-down materials are water or paraffin wax, which both contain hydrogen. The hydrogen atom has about the same mass as the neutron, and when they collide the result is usually that both move after the collision so that in each collision the neutron will lose about half of its energy. Hence a fairly small amount of water or wax is sufficient to bring the neutron almost to rest. It will ultimately travel at the same speed with which the hydrogen atoms themselves are moving about because of their irregular heat motion. A substance which reduces the speed of the neutrons in this manner is usually called a 'moderator'.

Attempts were then made to see whether a system made up of uranium and some hydrogen compound such as water could give a chain reaction. Many independent investigations, which were then already carried on in secrecy, were not successful in achieving this. The chief obstacle is that the hydrogen captures some of the neutrons, forming the so-called 'heavy hydrogen' which consists of one hydrogen nucleus and one neutron. This, together with the neutrons absorbed by the uranium itself, means a considerable loss, so that the 'multiplication factor' k may never exceed one.

An improvement first suggested by the group in Paris, and later independently by many other workers in the field, consisted in arranging the materials in layers or in some other regular pattern, keeping the uranium separate from the slowing-down substance. The point here was that uranium is particularly liable to capture neutrons at intermediate velocities, which the neutrons would reach in the course of being slowed down. By mixing the materials less intimately one could ensure that neutrons had less chance of meeting a uranium atom while they were in the process of slowing down to the final velocities. This gave some improvement, but still no success in establishing a chain reaction.

The work then turned to other substances in place of hydrogen which were not as light and, therefore, were not as efficient as moderators, but which in proportion absorbed even fewer of the neutrons. Attempts were made to use for this purpose pure carbon in the form of graphite or heavy water, i.e., water in which the hydrogen is replaced by 'heavy hydrogen'. We now know that both methods are possible, but both are extremely difficult. In the case of the graphite system, the difficulty is that even in ideal conditions the multiplication factor k is only barely greater than one, and any impurity in the graphite or in the uranium is liable to introduce sufficient absorption to reduce it below one and make the whole system unworkable. For the same reason the loss of even a small fraction of the neutrons through the surface would be serious. One has, therefore, to make the system very large so that the numbers escaping through the surface should represent only a small fraction of the number of neutrons present in the 'pile', as such a structure is called.

This graphite pile was the one chosen for the American project during the war. After some preliminary work had given encouraging results the group of scientists at Columbia University, which included Fermi, succeeded in proving that given enough graphite and uranium of sufficient purity a chain reaction could be achieved, and later when the work was being carried on at the 'Metallurgical Laboratory' at the University of Chicago the first chain reaction started to work in February 1942. Already at that time the work was going ahead on bigger installations: the Clinton pile, which was still an experimental plant but could work at some reasonable power and produce material for experimental purposes, was put into operation in 1943, and large-scale plants of considerable power were later completed at Hanford near the North Pacific coast.

The alternative possibility of using heavy hydrogen as a moderator makes less exacting demands on the purity of the materials and offers economy in design, but the heavy water required for its construction is very costly, since it has to be separated from ordinary water, in which it is present only as a small impurity (see the article on Isotope Separation). As an insurance against failure of the other methods, work on the extraction of heavy water was also continued, and a joint Anglo-Canadian team studied the possibilities of a reactor based on heavy water. Since the end of the war the construction of piles of this type has also been completed successfully and there is now a large heavy water pile in operation at the Canadian research station at Chalk River, Ontario, as well as an experimental reactor in the United States.

5. *The Role of U235: Explosion*

In the meantime there was a parallel development based on the following consideration. From the observations on the process of fission, Bohr had concluded that, for the capture of neutrons and for fission by slow neutrons, two different kinds of uranium were responsible. It is known that uranium atoms are of different kinds, distinguished chiefly by their weight, the most common one being the heaviest with a weight of 238 units, a rarer one, of which there is only one to every 140 of the heaviest, having a weight of 235 units.

More about these 'isotopes' can be found in the article on Isotope Separation. Bohr concluded then that only the rather light isotope, uranium-235, could be split by slow neutrons, whereas most of the capture of neutrons was due to the heavy one. It was immediately clear that it would be very much easier to release atomic energy if one could obtain a quantity of the rare isotope uranium-235 separated from the other; but it was well known that to separate the isotope of so heavy an element was a job that went far beyond the wildest dreams of anybody thinking about laboratory experiments; no-one seemed prepared to take such a suggestion seriously.

This situation changed, however, when people started to think out in earnest what one could do with separated uranium. This consideration must have occurred to many people. It is natural for the present writer to think of the discussions of Frisch and Peierls at Birmingham, in which they tried to guess, following Bohr's ideas, the properties of uranium-235. As explained before, a slow neutron had an appreciable chance of causing fission in ordinary uranium, and this chance, according to Bohr, was entirely due to the uranium-235 contained in ordinary uranium. Separated uranium-235 would obviously give the neutron a much better chance, and, at the same time would eliminate almost entirely the chance of capture. In other words, almost every one of the neutrons would be able to split a uranium atom, and as long as the number of neutrons resulting from this was well above one, the success of the chain reaction was practically assured. If the neutrons are not slowed down they have to travel somewhat further before they make a collision, but since they will split the uranium in a good fraction of the collisions they make, this will still only mean that one has to employ an amount whose dimensions are not greatly in excess of the 'mean free path'. Moreover, if we are using pure uranium-235, the rate at which the chain builds up is very much greater than with the other process described before. In both cases the neutrons have not been slowed down and, therefore, are still moving with high velocity and waste less time between collisions, and also, because the multiplication factor may now be well above one, fewer generations are required to reach any definite multiplication.

This distinction is important because, if we would let the reaction with slow neutrons go on without stopping it, it would take enough time to allow the material of our system to be molten and eventually vaporised as a result of the high temperatures caused by the energy we are setting free, and as the system expands it will occupy greater space, thereby increasing the chance of neutrons finding their way out without making collisions, and quite soon the multiplication rate will have dropped below the critical value of one. This will, in fact, happen when not much more energy has been liberated than is necessary to vaporise the uranium and whatever goes with it, so that an explosion caused in this way, while very powerful, will release only a very small part of the energy contained in the uranium. If, on the other hand, we could cause a reaction with fast neutrons in a system with a multiplication factor well above one, the time in which the reaction is complete is so short that even if the material is completely vaporised it has not time to move very far before a substantial part of the reaction is complete. Actually, the fraction of the available energy that can be liberated by an explosion of this kind depends a good deal on the arrangement of the material and the container that surrounds it, and a discussion of some of these factors will be found in the article on 'The Physics of the Bomb'.

But even the crudest estimate of the power of such an explosion made it clear that its military value would justify an extreme effort in attempting the separation of the uranium isotopes, and that this should be tackled, not from the point of view of laboratory experiments, but from the point of view of an industrial process. The question of what is involved in this is discussed in the article on 'Isotope Separation'.

6. *Plutonium*

About the same time, another line of approach was found to the same end. We have previously seen that one could produce a chain reaction with slow neutrons, but that of these neutrons a fraction will not cause fission but will be captured by the uranium. Whenever this happens the uranium nucleus of weight 238 will be turned into a new isotope of weight 239 by the addition of the neutron. It turns out that this new nucleus, for greater stability, needs a higher charge, and it therefore proceeds by the process known as beta-transformation to emit in succession two electrons, each carrying one unit of electrical charge and very little mass. Thereby the nucleus becomes, instead of a uranium nucleus with charge 92, the nucleus of charge 93 called neptunium, and then 94 or plutonium. This new element, plutonium, was discovered at Berkeley in 1940. From the laws of the behaviour of heavy nuclei, one had to expect that plutonium would have very similar properties to the light isotope of uranium and it was, therefore, likely that it would be equally suitable for use in a military weapon. At first very small amounts of this element were produced in the laboratory, essentially by the wasteful methods outlined in the beginning of this article, and with these it was possible to confirm that plutonium, like uranium-235, had a strong tendency to split when hit by a neutron.

This leads to a scheme that might, at first sight, sound more fantastic even than a large-scale separation of isotopes: a slow neutron reaction is allowed to proceed in a controlled way, so as not to destroy the plant; in this system some neutrons cause fission in uranium-235, thereby producing the new neutrons needed to continue the reaction, and also producing energy which has to be disposed of and could, in principle, be utilised. Other neutrons will convert some of the uranium into the new element plutonium. This has somewhat different chemical properties from uranium and when enough of it has been accumulated one can extract it from the uranium by ordinary chemical methods.

The plutonium obtained in this way is the second of the powerful atomic fuels known, and the production of plutonium was, in fact, the purpose which justified the effort spent on the construction of the large plants at Hanford to which we have referred. It is by now common knowledge that the many difficulties in the way of extracting the small quantity of plutonium from the large mass of highly radioactive uranium were successfully overcome, and that practically pure plutonium was available for the first test of an atomic explosion and was used in one of the two weapons dropped in Japan.

7. *Constructive Applications*

In this survey we have followed largely the historical approach, and for that reason we were almost exclusively concerned with the military use of atomic energy. But the new discoveries contain important possibilities of constructive value as well as means of destruction. The most obvious of these is the production of power, either by piles using ordinary uranium or by small reactors using the more valuable concentrated fuels, i.e. uranium-235 obtained by isotope separation, or plutonium from a large pile. In fact, in a sense the large piles constructed for plutonium production have also been producing power as a by-product. However, it was not practical to build them in such a way that the power could be put to any practical use, the main reason being that atomic energy is liberated in such piles in the form of heat and the conversion of heat to power (as in a steam engine) is impractical unless the system is at a reasonably high temperature. Practical difficulties have so far prevented the building of a pile which would be capable of withstanding a temperature at which, for example, one could economically raise steam. However, there is no doubt that these practical problems will ultimately be solved, and the progress along these lines is discussed in the article on 'Nuclear Reactors'.

It will be seen from that article that the main development

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is likely to consist in large-scale reactors which may at some time in the future be used to replace some of our ordinary power stations. Even with the use of the expensive concentrated fuels an atomic reactor will never be a very small unit if only because the dangerous radioactive radiations from it force one to use heavy shields of concrete or similar material.

Whether atomic power will ever be a major factor in the power resources of the world depends partly on the cost of atomic power stations and partly on the availability of raw material. The world resources of uranium are discussed in the article by Professor Tilley. An important unknown in this is the extent to which the raw material can be used up, and this depends on the question of 'breeding', i.e. the possibility of replacing the material one has consumed by plutonium or other atomic fuels produced at the same time. This process of breeding is also discussed in Sir John Cockcroft's article.

However, in addition piles produce as a by-product a large variety of new radioactive substances which have already proved of enormous value in many fields. The articles on radioactive isotopes in biology and industry and on medical uses will outline the vast new possibilities made available by these materials. It is important to realise that as far as we can see the amount of such materials needed for all applications one can at present foresee is very small compared to what one would obtain as by-products if one were to go in for atomic power on a large scale. In fact, as Sir John Cockcroft points out in his article, the disposal of surplus radioactive materials may prove quite an embarrassing problem for the power programme.

8. *The Sun and the Hydrogen Bomb*

Recently public interest has been focused on the production of atomic energy by quite a different process. We have seen before that in ordinary conditions charged nuclei are useless as projectiles in causing nuclear reactions, because in

passing through matter they tend to lose their energy before they have had a good chance of hitting another nucleus. This changes when the temperature of the matter is extremely high. Then all the atoms in this matter are in very rapid and irregular motion and, like a child trying to push its way through a crowd of people all running around at great speed, a particle will not be stopped by collisions with other atoms but will itself be kept in rapid motion.

If the motion it acquires in this way is fast enough to overcome the repulsion between the electrically charged nuclei, the close collision between two nuclei may become quite a common phenomenon. Such nuclear reactions caused by high temperatures are usually called 'thermonuclear reactions'.

These are the conditions in the interior of the sun and other stars. We find there temperatures of the order 20,000,000° C. and at those temperatures the velocity of a proton is high enough to overcome its repulsion by another proton or other light nucleus. In those circumstances it may happen that light nuclei combine and in this process energy is released. This is because the most stable form of nuclear matter is that of elements of medium weight. In combining hydrogen atoms until we reach helium and on to still heavier atoms, we go towards elements of greater stability. This is the reverse of the gain of energy by breaking up the heaviest element such as uranium in which also we change from a less stable to a more stable form of matter and thereby gain energy.

In the sun the most important reaction is a rather complicated one in which the net result is to turn hydrogen into helium.

It actually depends on the presence, besides the hydrogen, of other elements, in particular carbon, which can capture protons and hold them for long enough for the beta-decay to take place. The carbon atom merely serves as the 'reaction vessel' in which protons are turned into neutrons and is not used up in the reaction. It acts as what the chemists call a 'catalyst'. This process is exceedingly slow in the sun. It takes many millions of years to transform in this way any appreciable fraction of the hydrogen which is present.

To reproduce this process artificially one must in some measure imitate the conditions in the interior of the sun, including in particular the extremely high temperatures and pressures. The temperature necessary may, in fact, be higher than in the sun because one wants to see results more quickly than in astronomical periods. It does not, of course, follow that one must use just the same kind of reaction that takes place in the sun; a great many different combinations of light elements can in principle be used, and one would want to use that which needs the least temperature to start and releases as much energy as possible so as to maintain the high temperature once the process has started. One way that immediately suggests itself for reaching the necessary high temperatures is the use of the intense heat produced by an atomic bomb.

A weapon based on the ideas sketched in this section is now commonly referred to as the 'hydrogen bomb' or 'super bomb'. Whereas in utilising the uranium fission as an energy source we can choose between a controlled reaction useful as a source of power and an instantaneous explosion good only for destruction, the first alternative does not seem to be possible with thermonuclear reactions. The point is that it is difficult enough to reach and maintain the necessary high temperatures even for a short instant. To produce a slow reaction one would have to maintain them steadily for some time, and since there exist no materials capable of withstanding temperatures even remotely approaching those which would be necessary, one can dismiss for the present any suggestion of the controlled release of power from this source as quite impracticable.

[*Section* 8 *added February* 1950]

2

Atoms and Nuclei

H. A. BETHE

ALREADY the ancient Greeks knew the concept of the atom. They argued that if you take a piece of matter of any kind and divide it again and again into smaller parts you finally come to an end, to parts so small that they can no longer be divided by any means. These they called atoms, which means indivisible things. Of course the idea that matter consisted of atoms was not universally held; many Greek philosophers believed that subdivision *could* be continued indefinitely and that there were no atoms. Neither side had any evidence in favour of its beliefs, and it was only in modern chemistry and physics that the atomic hypothesis got a solid foundation.

Modern chemistry began with the researches of the French chemist Lavoisier and his contemporaries at the end of the 18th century. They showed that most of the common substances can be decomposed by chemical action into simpler substances which they called chemical elements. Since then 88 different chemical elements have been found in nature. They include hydrogen and oxygen, the two elements contained in water; nitrogen, which with oxygen forms the main part of air; carbon, one of the fundamental elements in the human body and other organic matter, and many others. Metals like iron, copper, gold, mercury are chemical elements.

If a piece of an element, let us say a piece of iron, is divided into small parts and this division is continued, one finally arrives at small indivisible units which are the atoms of modern chemistry. If a piece of an ordinary chemical substance, a 'chemical compound', is subdivided in the same way and not subjected to chemical action, we finally arrive at the smallest unit which still has the properties of the compound and which is called a *molecule.* All facts of chemistry can be explained by assuming that the molecule of any given substance is composed of a definite number of atoms of various kinds. The number of atoms in a molecule is usually quite small; for instance the water molecule contains 2 atoms of hydrogen and 1 atom of oxygen, which is indicated by its chemical formula, H_2O. A molecule of ordinary table salt contains 1 atom of sodium and 1 atom of chlorine, NaCl. Only if we go to the more complicated organic molecules do we have many atoms in one single molecule.

Chemistry was able to show that the atom of each chemical element has a definite weight called the *atomic weight,* and to determine this *atomic weight.* For instance, when water is decomposed into its elements, it is found that in every case 16 grams of oxygen are formed for each 2 grams of hydrogen. With the chemical formula H_2O, this means that one atom of oxygen must weigh 16 times as much as one atom of hydrogen. It was found in this way that hydrogen had the smallest atomic weight, and this atomic weight was therefore used as a unit. The atomic weights of the elements range from 1 for hydrogen to 238 for the heaviest atom, uranium.

It was just the fact that decomposition of each chemical compound always led to the same proportions of the chemical elements that gave support to the atomic hypothesis. No matter how small an amount of water is decomposed, the ratio of hydrogen and oxygen is always the same; therefore dividing a water drop into smaller droplets does not change its chemical composition. It is a most natural assumption that this composition is determined by the fact that the smallest units of the elements, the atoms, combine in some simple way to form the molecules, the smallest units of the chemical compound. It required very long study to determine the number of atoms of each kind in a given chemical molecule; to show, for instance, that water contains two hydrogen atoms for each oxygen atom rather than equal numbers of each. This study was helped by the integration of many different facts of chemistry and physics.

In chemical reactions the molecules change their composition but the atoms always remain the same. In a simple reaction such as

$$HCl+NaOH=NaCl+H_2O$$

the properties of the end products of the reaction, salt and water, are completely different from those of the initial substances, hydrochloric acid and caustic soda. However, the number of atoms of each kind is preserved; we have in the beginning two atoms of hydrogen, and one each of oxygen, sodium, and chlorine, and we have exactly the same atoms in the end.

Chemistry had thus answered the problem of the alchemists. The alchemists' aim was the change of cheap metals like lead or iron into expensive ones like gold. Chemistry stated that this was not possible; each of these metals was an element and it was not possible to change the number of atoms of each element.

Two remarkable discoveries were made when the atomic weights of the various elements became accurately known. The first of these was the periodic system of the elements which was discovered by Mendeleyev. He found that if you order the elements according to increasing atomic weight, then their chemical properties will repeat periodically. For instance, some elements are known as alkali metals: they include the common elements sodium and potassium. The element following an alkali metal in atomic weight will invariably be an 'alkaline earth' like magnesium and calcium, while the element preceding an alkali metal is always a noble gas like helium, neon and argon.

The second fact was that most atomic weights turned out to be near integers; this rule was even more accurately fulfilled when the atomic weight of oxygen was taken to be exactly 16, rather than that of hydrogen as exactly equal to 1.

With 16 as the weight of oxygen, the weight of hydrogen turned out to be 1.008, sufficiently close to 1. There were some notable exceptions to the rule, such as chlorine, which has an atomic weight of 35.5, but the rule was sufficiently generally fulfilled to draw the attention of chemists.

Toward the end of the 19th century it became possible to determine the number of atoms in a given mass of material, or the weight of an individual atom. This was made possible by the kinetic theory of gases, which explains for instance the pressure of air by the motion of the molecules of the air. The best measurements made since then show that, for instance, an ounce of water contains about a billion billion* molecules. This is an enormous number; so the size of one individual atom is exceedingly small. About one hundred million atoms laid side by side are an inch long.

The atom of 19th-century chemistry was like the atom of the ancients, indivisible and unchangeable. The first sign of its divisibility came at the end of the century, when the English physicist Sir J. J. Thomson described how small electric particles can under certain conditions come out of atoms. These small particles he called *electrons;* they were all found to be alike in charge as well as in weight. The charge of the electron is negative and is the smallest electric charge that has ever been observed. It is therefore used in physics as a unit of charge. The weight of an electron is much smaller than that of the lightest atom; about 1840 electrons weigh as much as one hydrogen atom.

If there are negative charges in the atom there must also be positive charges, because the atom as a whole is electrically neutral. In 1910 Lord Rutherford discovered the details about the positive charge. He found that the positive charge of each atom was concentrated in a very small space and was intimately connected with the largest part of the weight of the atom. This large mass carrying the positive charge he called the *atomic nucleus,* and thus was established the present picture of the atom: a massive nucleus, positively charged, surrounded by a number of negatively charged electrons.

The size of the atomic nucleus is exceedingly small. The diameter of the atom is about 20,000 times greater than that of the nucleus. The size of the electron has not been satisfactorily determined, but is certainly not greater than that of the nucleus. Therefore the atom consists mostly of empty space, and if you could fly through atoms you would only occasionally meet either an electron or a nucleus.

The weight of the atom is the sum of the weights of the nucleus and of the electrons, and since the electrons weigh practically nothing, the weight of the nucleus is almost the total weight of the atom. The electric charge of the nucleus, which is positive, must just compensate that of the electrons around it. We know that all electrons have the same charge, which we may call $-e$; we therefore find that the charge of any nucleus must be a multiple of the unit positive charge $+e$. How many units of positive charge a given nucleus contains can be determined by experiment, the most accurate way being the wave-length of the characteristic X-rays which are emitted by the atom. In this way it is found that the hydrogen nucleus has just 1 unit of charge; the next heavier nucleus, helium, 2 units; carbon, nitrogen, and oxygen have respectively, 6, 7, and 8 units of charge, and the heaviest nucleus, uranium, has 92 units. It turns out that the *nuclear charge* increases from element to element together with the atomic weight. Each element has its characteristic nuclear charge, and one can number the elements conveniently by the number of units of charge carried by their nucleus.

We have mentioned above that 88 chemical elements have been found in nature. This is slightly less than the 92 for which there would be room according to the different possible values of the nuclear charge. The remaining four elements, of charge numbers 43, 61, 85, and 87 do not occur in nature because their nuclei are unstable. Discovery of some of these has been claimed repeatedly but these claims have always been found to be false. The elements can, however, be produced by nuclear transformation, as we shall see later, and their properties have been investigated.

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*A billion is used here according to the English usage, meaning a million million. In American usage this number is called a trillion.

A nucleus which has Z units of positive charge will assemble around itself Z electrons in order to form a neutral atom. If by some chance the atom should have lost one or several of its electrons it will eagerly attract other electrons which may happen to be in its surroundings, and will recombine with these electrons to form a neutral atom again. This is due to the strong electric attraction between the negative charge of the electron and the positive charge of the remaining atom.

In 1914 the great Danish physicist Niels Bohr developed a complete theory of the atom on the basis of Rutherford's ideas and of the quantum theory. He showed how to calculate the motion of the electrons and how to find from this motion the properties of the atoms. In its present form, this theory is believed to give a complete description of the properties of the atoms. It permits one to calculate the wave-length of the spectral lines which the atoms emit, and to predict their chemical properties. The theoretical predictions are sometimes difficult to make because of the very complicated mathematics involved; but whenever the calculations have been performed, their result was found to agree with experiment to an amazing precision, which may be as good as 1 part in a million.

The properties of the atom can be predicted merely from the knowledge of the number of electrons in the atom. It is therefore this number of electrons which determines the chemical behaviour; it determines, for instance, that 2 atoms of hydrogen will combine with 1 atom of oxygen to form a water molecule. The number of electrons in turn is determined by the nuclear charge, so it is ultimately the nuclear charge which determines the properties of a chemical element. On the basis of Bohr's theory of atomic structure it was possible to explain in detail the periodic system of the elements discovered by Mendeleyev.

The electrons of an atom can be removed without very great difficulty, for instance in an electric spark. This process also goes on in very hot gases, for instance in stars, and also in the cathode of a radio valve in which the electrons are separated from the atoms of the cathode. The removal of electrons requires considerable energy because of the electric attraction between the electron and the positively charged remainder of the atom; it is therefore not a source of energy. It might properly be called atom splitting, but it is not given this name in common usage.

The atom of Rutherford and Bohr is divisible and has a structure. However, the nucleus of this atom might still have been indivisible. This assumption, however, turned out to be false. Even before Rutherford's discovery, and in fact forming an important tool in that discovery, it had been found that some of the heaviest atoms emit strange radiations called *radioactivity*. These radiations come from the atomic nucleus. The uranium nucleus and the nucleus of the well-known element radium are examples. Both of these emit particles which carry two positive charges and can be shown to be identical with the nuclei of helium. By emitting these particles, which are known as alpha particles, the element radium, which is a solid metal, turns into a gas called radium emanation. The charge of the nucleus of emanation is two units less than that of the radium nucleus, just the two units which were taken away by the alpha particle. The helium atom has an atomic weight of 4 units, and it turned out that the nucleus of emanation had an atomic weight 4 units less than that of radium.

Other radiations also came out of the radioactive nuclei, so-called beta rays. These are ordinary electrons carrying one negative charge and with practically no mass. Accordingly the nucleus after emitting them had gained one unit of positive charge and had not changed its atomic weight.

When first discovered, the phenomena of radioactivity seemed restricted to the very heaviest nuclei, namely those carrying a charge of 82 units or more. Moreover, the splitting of these nuclei occurred spontaneously, without any external influence and independently of such influences. It is known as natural radioactivity or as spontaneous radioactive decay. A completely new perspective was opened in 1919 when Lord Rutherford used alpha particles to bombard the nuclei of nitrogen. He found that occasionally a completely new particle resulted from such a collision, which turned out to be a hydrogen nucleus, a so-called proton. The nitrogen nucleus itself was transformed in this process into a nucleus of oxygen.

By this discovery the concepts of classical chemistry were profoundly changed – although, of course, the *practical* conclusions of chemistry were unaffected. It was now possible to *change one chemical element into another by bombarding its nucleus.* Not only the atom but even the nucleus had been shown to be divisible and to contain yet smaller particles.

What these particles were was revealed only in 1932 when Sir James Chadwick discovered still another type of particle coming out of light nuclei bombarded by alpha particles. These new particles had no electric charge; they were electrically neutral and were therefore called neutrons. They had very nearly the same weight as protons, the nuclei of hydrogen.

It is now well established that the fundamental units of an atomic nucleus are neutrons and protons. The number of units of *charge* in the nucleus is equal to the number of protons contained in the nucleus, each proton contributing one unit of positive charge. The atomic *weight* is approximately equal to the sum of the numbers of neutrons and protons.

Considerably before the discovery of the neutron it had already been found that there were several species of nuclei of the same element. These species are called isotopes. All isotopes of one element have nuclei of the same nuclear charge, because it is the nuclear charge which determines the chemical properties of an element. The isotopes differ, however, in their atomic weight. According to our present ideas, then, all isotopes have the same number of protons in the nucleus but the number of neutrons is different for different isotopes.

The discovery of isotopes gave the explanation why certain chemical elements have atomic weights which are not integers. For instance, the element chlorine was found to consist of two isotopes of atomic weights 35 and 37, present in the ratio of about 3 to 1 in natural chlorine. This makes the atomic weight of natural chlorine 35.5.

Almost every chemical element was found to consist of several isotopes. Even hydrogen has two isotopes, one of weight 1 and one of atomic weight 2. However, the latter, called heavy hydrogen or deuterium, is present only in minute amounts, namely only about 1 part in 5,000 of natural hydrogen. Some elements have very many isotopes; tin for instance has 10. When the weights of the individual isotopes were determined they were found to be much closer to integers than the ordinary chemical atomic weights had been, but even they were not exactly integers.

We have said before that nuclei consist of protons and neutrons. These neutrons and protons, or nuclear particles, are held together in the nucleus by the strongest forces known. The forces are about a million times stronger than the electric forces that hold the electrons in the atom. These forces are stronger than the chemical forces which hold together the atoms in a molecule. The chemical forces again are many times stronger than the elastic forces which hold together, for instance, a piece of steel – and everybody knows how difficult it is to tear apart a piece of steel.

There is a very convenient method of measuring the strength of the nuclear forces. This is based on Einstein's theory of the equivalence of mass and energy. This theory, which is a part of the well-established special theory of relativity, states that one gram of mass is equivalent to an enormous amount of energy, namely about 25 million kilowatt-hours. This is the output of a very large electric power plant, such as that at Boulder Dam, for one day.

The application of Einstein's theory to nuclei is connected with the fact that the atomic weights are not exactly integers. More precisely, a nucleus of oxygen which contains eight protons and eight neutrons, weighs nearly 1 per cent less than the separate protons and neutrons would weigh. According to Einstein's relation, this means that the oxygen nucleus contains less energy than the separate protons and neutrons, and in fact very much less energy, because the energy equivalent of even a small amount of mass is so large. Since the oxygen nucleus contains less energy, energy would be required to tear it apart into its protons and neutrons. The splitting of the oxygen nucleus into protons and neutrons would therefore not be a source of atomic energy, but would on the contrary require large amounts of energy to accomplish. The difference in atomic weight between a nucleus and the separate protons and neutrons of which it is made is a measure of the great strength of the nuclear forces.

All existing nuclei have this property of having less weight than the separate protons and neutrons of which they are made. Therefore in all nuclei neutrons and protons are bound together with strong binding forces. Very little is known about these forces except their great magnitude, and it is one of the most important and interesting problems of physics to explore the nature of the nuclear forces. It is sure that they are not electric in nature because electric forces are much smaller; and even less can they be explained as gravitational forces, which are smaller than nuclear forces by a factor of many billions of billions. Many theories have been made about the nature of the nuclear forces, but none of them so far has explained all known facts.

Energy is set free when protons and neutrons are brought together to form more complex nuclei. This is the principle by which the stars are supposed to generate their energy. In the stars, in effect, two protons and two neutrons are combined to form a nucleus of helium, a process which is connected with a great release of energy. This combination cannot take place directly, but only by means of a complicated sequence of reactions in which carbon and nitrogen nuclei serve as catalysts. These reactions go on in billions of atomic nuclei every second in the sun.

Energy can, at least in principle, also be released by the splitting of nuclei. Whereas all nuclei are lighter than the sum of the neutrons and protons of which they are made, the heavier nuclei have a greater weight than *some* fragments into which they might be broken up. So for instance, the nucleus of radium has a greater weight than the sum of the nuclei of emanation and of helium. This difference in weight is only about 1 part in 20,000, but it is sufficient to permit the emission of alpha particles from radium. The uranium nucleus, containing 238 nuclear particles, has a slightly greater weight than two tin nuclei, each containing 119 particles. The difference in this case is one part in a thousand, or one-tenth of 1 per cent, which is very substantial. Therefore, if there is any mechanism for splitting a uranium nucleus into two nuclei of atomic weight of around 100, then such atom-splitting will undoubtedly set free a good deal of energy. It will be recognised that this is exactly what happens in the process of nuclear fission, but we shall have to discuss some other problems before we can come to the problem of fission.

The structure of atomic nuclei was explored by transforming one nucleus into another. The first example was Rutherford's experiment transforming nitrogen into oxygen by bombarding the nitrogen with alpha particles. Several hundred such nuclear transformations have been observed, most of them in the 1930's. They are similar to chemical reactions, with the nuclei playing the part of the molecules, and the neutrons and protons playing the part of the atoms. The nuclei change their nature in a nuclear reaction, but the total number of neutrons and the total number of protons remain always unchanged.

A nuclear reaction is produced by bringing two nuclei into close contact with each other. One of these is usually a very light nucleus such as the nucleus of light or heavy hydrogen or the nucleus of helium, or it may be a neutron. If a charged particle (nucleus of hydrogen or helium) is used for the purpose, some difficulty is experienced because both the nuclei which are supposed to approach each other have a positive charge. It is well known that two positive electric charges repel each other, and these repulsive forces become very strong at the close distances to which the nuclei have to approach. To bring a positively charged particle in contact with the nucleus it is necessary to give that positive particle initially a very high speed. Then its velocity may carry it to the nucleus in spite of the strong repulsive forces. This is the reason why nuclear experiments require large apparatus to accelerate the particles to high velocity. The first such apparatus was successfully constructed by Cockcroft and Walton in the Cavendish Laboratory. At present the cyclotron, first constructed by E. O. Lawrence in California and the electrostatic generator, first constructed by Van de Graaff at the Massachusetts Institute of Technology, are the most commonly used types. They are capable of giving to a proton or other charged particle an energy corresponding to a potential difference of several millions of volts, and this energy is sufficient to disintegrate even the heaviest atomic nuclei known, i.e. nuclei with the greatest positive charge and therefore the greatest repulsive forces.

The neutron has been especially successful as a projectile to induce nuclear transformations. This is because it has no electric charge and can therefore approach atomic nuclei without any repulsive forces. For this reason neutrons do not need to have high energy; in fact very slow neutrons are often more effective than fast ones. The Italian physicist Fermi and his collaborators have been most prominent in investigating the nuclear reactions which can be produced by neutrons. There is only one point which makes the use of neutrons difficult: neutrons do not occur freely in nature as the atoms of hydrogen and helium do. Instead, neutrons have to be themselves produced in nuclear reactions, and

the number which can be produced is strictly limited in ordinary nuclear reactions.

There is another important difference between neutrons and charged nuclear particles, which concerns the mechanism of their passage through matter. Charged particles are subject to electric forces even if they do not collide with a nucleus but only pass through an atom. They are deflected easily, and they may also accelerate, by means of their electric forces, electrons which may in this way be ejected from their atoms. This ejection costs energy, which leads to a slowing down of the charged particle. Therefore, any charged nuclear particle loses energy quickly when passing through matter. The fastest particles which have been produced can penetrate only a fraction of a millimetre of solid material.

The neutrons, on the other hand, are not subject to any electric forces and can therefore not be deflected and cannot eject electrons from atoms. The only processes which happen to them are direct collisions with atomic nuclei. Because of the small size of the atomic nucleus a neutron can go a very long distance before colliding with a nucleus. In most solid substances this distance is between 1 and 4 inches.

Charged particles, therefore, even if they have initially a high energy, soon lose this energy and thereby the ability to cause nuclear reactions. Neutrons on the other hand make collisions only with atomic nuclei, and each neutron will in its lifetime cause some nuclear reaction or other, in the simplest case being just absorbed into an existing nucleus.

A particularly interesting result of the study of nuclear transformations was the production of new radioactive nuclei known as artificially radioactive nuclei, first discovered by the French physicist couple Joliot. All the artificially radioactive nuclei emit beta rays, either ordinary negative electrons, or so-called positive electrons which are similar to negative ones in all respects, except that they have a positive unit of charge instead of a negative one. About 200 such radioactive nuclei were discovered, and almost every chemical element was found to have at least two and often more isotopes which had this property of radioactivity. So for instance carbon, which in nature is found to have two isotopes of atomic weight 12 and 13, also has three radioactive isotopes, one of weight 10 and one of weight 11, both of which emit positive electrons, and one of weight 14 emitting negative electrons. Commonly, the weights of the radioactive isotopes are on both sides of the weights of the natural stable isotopes, but there are many cases known in which a radioactive isotope has a weight intermediate between the stable ones. Even the elements which have no stable isotope at all (elements numbers 43, 61, 85 and 87 as mentioned above) possess radioactive isotopes which have been produced and investigated.

What happens in the radioactive beta transformation is that a proton in the nucleus transforms itself into a neutron, with the positive charge going away in the form of a positive electron. Or conversely, a neutron may transform itself into a proton, one unit of negative charge being emitted in the form of an ordinary electron.

Aside from their scientific importance, the radioactive nuclei have been used to trace the fate of chemical elements in chemical reactions or in biological processes. It is very easy to detect the radioactivity by suitable electrical apparatus, and in all respects except the radioactivity, the radioactive atom will behave exactly like its ordinary isotopes. Therefore using radioactive isotopes amounts simply to putting an easily recognisable label on the atoms and then letting them undergo their ordinary chemical reactions.

All nuclear reactions investigated until 1938 had one thing in common: not only the particle initiating the reaction was small (a neutron, a proton or a nucleus of heavy hydrogen or helium, having an atomic weight of at most 4), but also one of the particles resulting from the reaction was always small, again having an atomic weight of 4 or less. All the remainder of the nuclear particles remained in the other nucleus resulting from the reaction.

For the first time in 1938 this picture was changed. A nucleus of uranium was split into two almost equal parts. This was done for the first time by the German chemist Otto Hahn who received the Nobel prize for 1945 for this discovery. Subsequent scientific development was very rapid, and it was shown that the uranium nucleus can be split up in many different ways, but in each case so that the weights of the two fragments were approximately equal.

As soon as this phenomenon, the nuclear fission, was discovered, physicists were able to calculate the energy release for this process by means of Einstein's theory. The nucleus of uranium is about 0.1 per cent heavier than that of the sum of the two fragments into which it can break up, and we have seen that this corresponds to a very great energy. This energy was measured independently by direct experiment and Einstein's relation was confirmed. Confirmation of this relation had previously been obtained in very many instances by the observation of ordinary nuclear transformations.

From the scientific point of view, the remarkable thing about nuclear fission was the splitting of a nucleus into two almost equal parts. From the practical point of view, however, the most interesting feature of fission is that this process is produced by bombarding a uranium nucleus with neutrons, and that in the process itself neutrons are again emitted. On the average the number of neutrons emitted in each fission is greater than 1; therefore the process gives the basis for a nuclear chain reaction.

If we take a large block of uranium-235, which is the isotope undergoing fission when bombarded by slow neutrons, the following events can happen. A neutron emitted by some source falls on one uranium nucleus and causes fission in it. Let us assume that two neutrons are emitted in this process. Let us further assume that the block of uranium is large enough for none of these neutrons to be able to escape, and also that no other process can be induced by neutrons in U 235. Then each of these two neutrons will again cause fission. In each of these fissions again two neutrons will be emitted, and the resulting four neutrons will again cause fission. This process will go on, always increasing the number of neutrons available. In each fission a large amount of energy is set free from the uranium nucleus. The process will finally stop in one of three ways; either (a) by some external control such as is being used in the neutron 'piles' described in another article in this book (p. 78), or (b) because the large amount of energy developed will cause a high pressure and thereby an explosion of the uranium – this is the basis of the atomic bomb – or (c) simply by the consumption of all the available U 235, on which naturally the process must stop.

In other articles in this book the application of the fission process both to a controlled reaction and to the construction of an atomic bomb is described. In the controlled fission reaction we have a very flexible, intense and cheap source of neutrons, many thousand times more powerful than the largest cyclotron. The properties of neutrons can be studied with much greater ease and precision than was possible before the discovery of fission and of the uranium chain reaction. Moreover, these neutrons can be used to produce in quantity new species of atomic nuclei, especially radioactive nuclei emitting beta rays. These nuclei are useful for biological, medical, chemical and industrial research. Finally the controlled nuclear chain reaction can be used to transform the uranium itself into plutonium, an element of nuclear charge 94 and not known on earth before. So now, at last, the dream of the alchemists is fulfilled, not only in theory but also in practice; one element can be transformed into another in quantities which are of practical importance.

3

Production of Atomic Fuel by Isotope Separation

R. E. PEIERLS, C.B.E., F.R.S.

1. *Isotopes*

Long before physicists had produced tangible proof of the existence of atoms, chemists had been familiar with the idea of 'atomic weight'. They knew, for example, that the weight of sodium that had to combine with an ounce of chlorine to make sodium chloride, or rock salt, was exactly twenty-three times as large as the amount of hydrogen that would combine with the same quantity of chlorine to make hydrocholoric acid.

We now know that this is because each atom of chlorine attaches itself in the one case to one atom of sodium, in the other case to one atom of hydrogen, and because an atom of sodium weighs twenty-three times as much as a hydrogen atom. By similarly weighing the amounts needed for different chemical combinations, it was thus possible to compare the weights of all atoms with the atom of hydrogen, the lightest of them all. It was then noticed that there were many atoms whose weight was very nearly equal to that of a whole number of hydrogen atoms, such as twenty-three in the case of sodium, and it was natural to think that this might be because all atoms were in some way built up of hydrogen atoms.

The work of Rutherford and his school showed, however, that things were not quite as simple as that; it was found that the heaviest part of the atom is a very small core, the nucleus, which is electrically charged. The charge is positive and the nucleus therefore forms a centre of attraction for the oppositely charged (negative) electrons. A hydrogen nucleus has a charge which is just equal and opposite to that of an electron, and one electron is therefore just sufficient to neutralise that charge, so that a hydrogen nucleus and an electron together form an atom which has no net charge, and therefore no strong tendency to attract other electrons. In sodium, on the other hand, the charge on the nucleus equals that of eleven electrons, except that it is positive, so that eleven electrons are required to neutralise it. The charge on the nucleus is also called the 'atomic number'. The atomic number of hydrogen is 1, that of sodium is 11. This number determines the chemical behaviour of the element, since all chemical changes are changes in the arrangement and motion of the electrons in the outer parts of the atom. Any small core carrying a positive electric charge equal in amount to that of eleven electrons will gather eleven electrons so as to neutralise its charge, and the whole will then behave in every respect like an atom of sodium, no matter what the weight or the structure of the core.

We can now see that a sodium nucleus cannot simply consist of protons (or hydrogen nuclei), since its weight equals that of twenty-three protons, whereas its charge equals that of only eleven protons.

The explanation became clear when Chadwick discovered the neutron, which weighs about the same as a proton, but has no charge. It was then evident that the sodium nucleus consisted of eleven protons and twelve neutrons.

At the same time this discovery explained the existence of 'isotopes'. It had been noticed that by no means all elements obeyed the rule that their atomic weight was nearly a multiple of that of hydrogen, and this, together with facts found in the relations amongst radioactive elements, had led Soddy to the idea that not all atoms of an element might be alike, but that some of them might have weights different from others, although their chemical nature was the same. Such atoms are called 'isotopes'.

From what we said before, this would clearly happen if there were nuclei that had different weights, but the same amount of electric charge; they would both be surrounded by the same number of electrons moving in exactly the same way, and they would undergo precisely the same chemical reactions with other elements. Since the nuclei consist of neutrons and protons, it is then clear that isotopes of the same element each contain the same number of protons (and hence have the same electric charge) but different numbers of neutrons.

The existence of such isotopes was definitely proved by means of the mass spectrograph, an instrument perfected by Aston. Its principle is roughly this: In an ordinary gas the atoms or molecules move in a very irregular fashion, since they collide with each other. If we reduce the amount of gas in a tube, however, by pumping some of it out, the remaining atoms will meet fewer atoms on their way with which they could collide, and they will therefore go in a straight line for longer stretches. It is possible to evacuate a tube to such a high degree that the remaining atoms will hardly ever collide with each other and that each atom has a good chance of travelling the whole length of the tube without disturbance.

If we now pass an electric discharge through such a gas (such as is used, for example, in the familiar tubes of neon signs, except that these are not as highly evacuated) some atoms will collide so violently with each other, or with stray electrons, as to have one or more electrons knocked off in the process. After this they are electrically charged, since the number of their electrons no longer equals that of the positive charges in the nucleus. Such charged atoms are usually called 'ions'. If the tube contains metal plates which are electrically charged, the ions will now be attracted or repelled by the plates; they will no longer move in straight lines, but go along a curved path inclined towards the plate carrying a negative charge.

Now compare two ions of different weights, each having lost one electron and therefore having the same positive charge. Let us further assume that both move with the same speed. Then the force due to the charged plates will pull on them to the same degree, but the heavier one, owing to its greater inertia, will respond less to this force and will, therefore, be deflected less from its straight path. The situation is the same as when we throw a wooden and a paper ball of the same size against a strong wind. The force of the wind on each of them is the same, but it has much more effect on the lighter one; the heavy one keeps going because of its greater inertia.

Hence, if we have arranged in the tube slits which make sure that all ions initially travel along the same straight line, we shall find them at the other end grouped according to mass, the heavy ones being closer to the straight path.

In actual practice the problem is more difficult because there is no simple way of making all ions start with the same speed. A faster moving ion will be deflected less than a slow one, and this would confuse the distinction between heavier and lighter ones. In order to overcome this difficulty, the actual mass spectrograph does not use merely the field of electrically charged plates to deflect the ions but, at the same time, provides a magnet outside the tube. This produces a magnetic field which also tends to deflect the ions, since a moving electric charge behaves like an electric current and is deflected by a magnetic field in the same way as the armature of an electric motor is set moving in the magnetic field of the motor.

The magnetic deflection depends on the speed. If, therefore, we arrange the tube in such a way that the deflection due to the electric plates is in a horizontal direction, that due to the magnetic field in a vertical direction, then if we catch an ion in the far end of the tube its horizontal and vertical deviation from the straight line tells us both its mass and its speed. In practice, the ions can be detected if a photographic plate is placed at the end of the tube. By running the tube for a sufficiently long time many ions will have reached the plate and will have blackened it at the points corresponding to certain masses, and by measuring the blackening some estimate can be obtained of the number of ions of each particular mass. There are other more sensitive ways of recording the arrival of the ions in each position, but we need not describe them here.

By means of this instrument,* Aston succeeded in showing that for most elements there existed, in fact, isotopes of several different masses. The mass of each isotope was nearly equal to a multiple of the hydrogen atom. Actually the masses were always found to be slightly less than a multiple of the hydrogen mass. But we shall not enter here into the explanation of this 'mass defect'.

The element uranium, with which we are here concerned, was in this way found to consist mostly of atoms of weight 238, but a weak isotope of weight 235 was found, of which there is approximately one atom for every one hundred and forty uranium atoms, and a third isotope of weight 234 is even a hundred times less frequent than 235. The isotope 235 is of particular value as an atomic fuel, as has been explained in the first article. The problem, therefore, arises of separating this isotope from ordinary uranium.

2. *The Problem*

One is faced with the question, then, how to separate uranium-235. In order to understand what this implies, the following illustration may help. Imagine one had a warehouse filled with tennis balls, all of the same size. A small portion of these, less than 1 per cent, are a little lighter than the rest, their weights being roughly in the ratio of 99 to 100. We are given the task of sorting out the lighter balls. The natural means of doing this, in the case of tennis balls, would be to weigh each ball on scales and sort out the ones of lower weight. But this necessarily involves handling each ball separately, and therefore is a procedure that cannot be adopted in the case of atoms. The next best thing would be to follow the method that is usually applied to separate grain from chaff – by throwing a continuous stream against the wind in conditions where the air resistance matters. The lighter objects for which the air resistance has a larger effect will land in a different place. If we want to apply this procedure to tennis balls, it is clear that we have to devise a very accurate gadget for throwing them, since we cannot expect more than 1 per cent difference in the distance they will cover, and also since there are so many more of the heavier ones that any slight error in aiming would make the heavier ones cover a wide range and completely swamp the place where the light ones should collect. Apart from the need for extreme precision this plan is quite feasible and, in fact, is one of the methods actually employed for the separation of uranium isotopes. If we consider the mass spectrograph described in the first section of this article, it is clear that it is, in principle, a device for separating isotopes along just such lines. However, as employed, for example, by Aston it is capable of handling only very small amounts of material. It had been regarded as a great achievement when Oliphant and his collaborators managed to obtain by means of a mass spectrograph quantities of isotopes that would not merely make impressions on a photographic plate, but that could actually be studied in their physical behaviour by the effects produced when strong beams of fast particles collided with them. Even so, these samples that it had taken a long time to collect were too small to be weighed; to make useful amounts of atomic fuel one would require many pounds, that is to say some thousand million times more than the greatest amount produced by a laboratory mass spectrograph. It is clear that, in order to get anywhere, one would have to construct a plant that would look very different indeed from an ordinary mass spectrograph, even though employing the same principle.

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*The actual arrangement used by Aston differs from the one here described, but it was based on similar principles.

This is, however, not the only way in which one might

proceed. The alternative is, in terms of our picture of tennis balls, to sort them by dividing the whole amount first in two parts by some device which would give some slight preference to the lighter ones. For example, we might put a large number of such balls into a box and shake the box for a long time. In this way, more light ones would be found near the top of the box than near the bottom, but it would not be practicable to go on until all the light ones had risen to the top because, by continued shaking, we would always mix up the balls again to some extent. We might, however, now take out the balls in the upper half of the box and proceed to shake those again. In the new, smaller box there would be more light ones at the top than near the bottom. By repeating this process again and again we could eventually reach a point where we had only light balls left near the top. At first sight, one would think that the best procedure might be just to take the upper half, in which case starting with 10,000 balls we would take the upper 5,000 out of the first box, shake these again and use the upper 2,500. Repeating the same procedure we would be left with 1,250 and so on. Clearly, if we go on in this way, we reduce very rapidly the amount of material we are handling and we would in this way recover only a small fraction of all the light balls we set out to find. This procedure, while possible in principle, is too wasteful in practice. To make it work we have to modify it by a trick well known to chemists who separate materials by distillation or other means, and that is using the 'cascade' principle.

By this we mean the following: We start again with 10,000 balls, shake them in the box and take out the upper 5000. However, we do not discard the lower 5000 which contain fewer light balls than the original mixture. Instead we also shake the lower half in a separate box. When this is done, the upper half of this box now contains more light balls than when we started and, in fact, contains about as big a fraction of light balls as in the original mixture. These we can, therefore, return to the starting point and carry them along with the next fresh supply. The lower half of this last box now contains even fewer light balls. It will be split again and the upper part will be brought to a point where it is the same mixture as the lower 5000 from the first separation. It can, therefore, be included when we again get a lower batch of 5000 from a fresh supply once treated.

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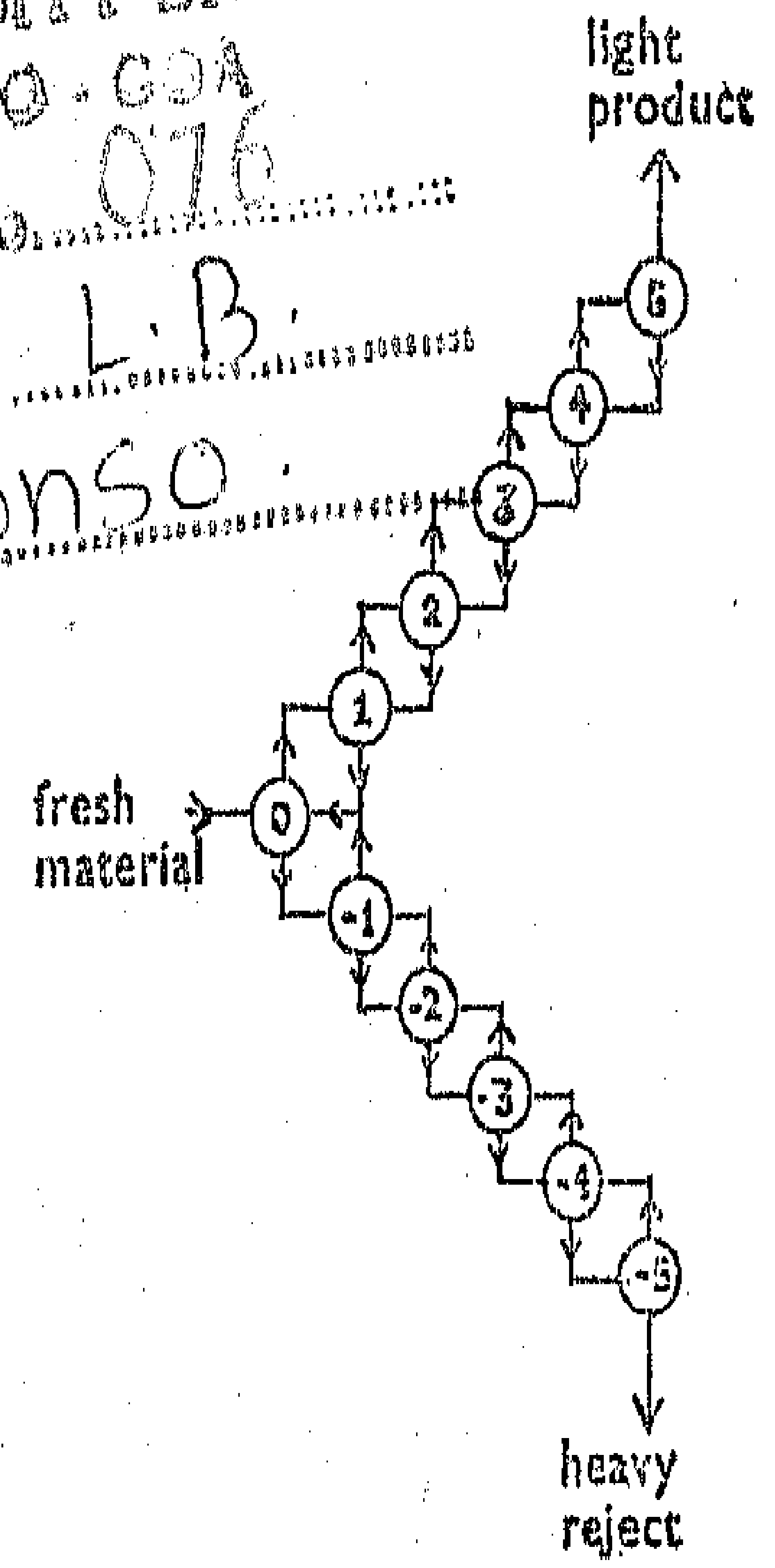


Fig 1.

The principle of this method now becomes clear, and the scheme of such a 'cascade' is illustrated in Fig. 1. Here each circle represents a 'stage', such as our process of shaking a box; the material used in the process is, for convenience of drawing, shown as entering from left and right. The 'light fraction' which is in our example the contents of the upper half of the box, after shaking, is shown to come out at the top, the 'heavy fraction' at the bottom.

The stages are numbered, 0 being the one handling fresh material; in stages 1, 2, etc., the material contains successively more of the light component, in those numbered -1, -2, -3, the material gets successively heavier.

Each stage is fed with the light fraction from the previous stage, and the heavy fraction from the succeeding stage, and these have just the same composition. For example, starting at stage 0, which contains natural material, the light fraction transmitted to stage 1 is somewhat richer in the light component, and therefore the material processed in stage 1 is somewhat richer than the natural mixture. The heavy fraction returned from stage 1 is, however, depleted by just the same amount by which the light fraction is enriched, and is therefore just back to the natural composition. The same is evidently true for any other stage. The diagram shows five stages above, and five below, the normal composition, but the scheme can be extended to as many stages as required. From the highest stage a product of the required concentration is obtained, the lowest stage discharges material which is depleted in the light component, and which, if necessary, can be made to consist only of the unwanted heavy component.

It is also clear that the amount of work to be done in going through this process may be very large, because in the stages in which the fresh supplies are first handled, we must handle, in addition, the amounts returned from other stages for retreatment, and if we were dealing, for example, with 100 stages in the process the amount that would have to be handled in the first stage might be about 100 times the original supply, since each ball on the average may be handed back 100 times for reprocessing before it finally finds its way to one of the end stages.

The cascade principle which we have described here has to be used whenever we work a process that does not sort out all light atoms completely in a single operation, as the mass spectrograph is capable of doing, but merely produces a mixture in which the number of light atoms has been slightly increased. There are many different ways of producing such a slight enrichment, and most of them have been known for a long time, but had never been used on anything but a very small scale. We shall describe some of these methods in the next section.

3. *Methods of Isotope Separation*

The first element for which isotope separation had been carried out on a commercial scale was hydrogen, although it was one of the last elements in which the existence of isotopes was proved. In addition to the common hydrogen atom of weight 1, which in fact we used as a standard for comparison with other atoms, it was found by Urey and his collaborators that a very rare isotope of weight 2 existed. Ordinary hydrogen contains only one heavy hydrogen atom to every 5000 atoms of weight 1, and for this reason the heavier isotope had escaped detection for a long time.

The isotopes of hydrogen represent a rather exceptional case, because the difference in weight of the two isotopes is very large, the one being twice as heavy as the other. As a result, it is possible to detect differences even in the chemical behaviour of the two isotopes and it is, therefore, often customary to talk of the heavier atoms as though they made up a separate chemical element that is called 'deuterium'. This would seem to be in contradiction to the fact which we noted before, that the chemical action of an atom depends merely on the charge on its core and that, therefore, isotopes ought to be quite indistinguishable in chemical behaviour. The explanation is as follows: Consider a chemical compound of hydrogen and some other element, say the combination of 2 hydrogen and 1 oxygen atoms into a water molecule H_2O. This molecule forms because there are attractive forces between the oxygen and hydrogen atoms, which tend to put the hydrogen atoms into positions adjacent to the heavier oxygen atoms; we might think of the molecule as one of those figures that modern sets of toys encourages children to make up – a big sphere in the centre with two small spheres joined to it by little sticks, the whole being fixed together quite rigidly. However, modern atomic theory teaches us that light particles have a dislike to staying fixed in a permanent position. For this reason, for example, electrons, which are extremely light, are never found in any definite place within the atom, in particular not near its centre, in spite of the electric attraction, but roam round over a region of considerable extent. This same tendency still exists for hydrogen atoms, although to a much smaller extent, and has the result that the hydrogen atoms in a water molecule will not stay in fixed positions, but will wobble a little in the neighbourhood of their equilibrium positions. This phenomenon is usually referred to as 'zero-point vibration' to distinguish it from the motions of the atoms that are caused by heat, whereas the motion described here persists even at the absolute zero of temperature. Now, since the phenomenon is more pronounced for lighter particles, the zero-point motion will be stronger for ordinary hydrogen atoms than for heavy hydrogen. Therefore, a molecule of 'heavy water' will differ from an atom of ordinary water by having less vibration in the heavy hydrogen, although the chemical forces are the same in each case. This means that the ordinary water molecule is a little less stable and can be broken up a little more easily by action from outside than the heavy water molecule. This fact is the basis for a number of different methods of separating heavy water from ordinary water. Historically, the first process to be so used was the electrolytic method which was adapted to this purpose by Urey. Urey noticed that if water is split into hydrogen and oxygen by passing an electric current through it, the hydrogen gas so collected contained a somewhat lower proportion of heavy hydrogen than the original water, whereas the remaining liquid water was somewhat enriched in deuterium. In principle one could apply the cascade process to this method, but in this case, since the raw material is plentiful, it is best to start by electrolysing a very large quantity of water until only a small fraction of it is left. This will be well enriched in heavy water and make a good starting point for the cascade process. Actually, such residues of large quantities of water that has been electrolysed are found in many commercial electrolytic plants, and all commercial processes for the production of heavy water start from such residues.

We might note in passing that the property which makes the production of heavy hydrogen fairly convenient in fact delayed its discovery, because the first work on mass spectrography that was done with a view to looking for isotopes of hydrogen had been done with hydrogen produced by electrolysis, and we have seen that such gas is particularly poor in heavy hydrogen.

The question may now be asked whether the same principle can be applied to other elements and in particular to uranium. Indeed a search was continued for a long time for chemical methods that could be used for the separation of the uranium isotopes, or for chemical compounds which might be slightly more or slightly less stable according to the isotopes of which they were made. No such process was found, and it is not surprising that this should be so, because, as we have seen, the only difference in the chemical behaviour of isotopes is due to the persistent wiggling or zero-point motion of the atoms. This effect gets progressively smaller as we go to heavier atoms. In uranium, whose atoms weigh 238 times as much as hydrogen, this motion is very much weaker and, moreover, since the atoms differ only so slightly in weight (3 parts in 238) this already very weak motion is almost the same for both isotopes. In addition, any chemical effects produced in this way are noticeable only at very low temperatures, at which the heat motion of the atoms is not larger than the 'zero-point vibration'. In hydrogen, where the zero-point motion is still fairly substantial, this causes no difficulty; but, in uranium, it would force one to go to temperatures so low that all known uranium compounds would be frozen and would not undergo any chemical reactions at all.

Chemical methods can be applied to some of the lighter elements if one desires to separate their isotopes, but with increasing atomic weight the method gets increasingly more difficult, and is already quite impracticable for atoms of medium weight.

Once such chemical methods have been ruled out, we are left chiefly with mechanical devices. The simplest of these, in principle, would be to sort atoms by their weight, rather like the picture of shaking tennis balls in a box which we discussed in the previous section. One might think, for example, of a tall column of some suitable gaseous or liquid compound of uranium, which was left standing until the light uranium could be skimmed off the top like the cream from a milk bottle. No doubt this method would work in principle, but it is made impracticable by two facts. The one is that the heat motion of the atoms (like our continued shaking of the boxes) tends to mix up the atoms again and therefore to undo the effect of the different weights. Hence we would need, for complete separation, a column many miles high. For example, the oxygen and nitrogen contained in ordinary air consist of molecules whose weight differs by two units, i.e. by almost as much as the uranium isotopes. Nevertheless, they do not get appreciably unmixed in the atmosphere between sea level and say 10,000 feet up. Otherwise, there would be no oxygen left on high mountains and life there would be impossible.

The height which is required for such a column would depend on the temperature. If we cool the whole column, the heat motion is less and the atoms will sort themselves out over a smaller height difference, but we cannot go far this way because no liquid uranium compound is known below room temperature, and gaseous compounds condense unless they are kept at such low pressures that the whole amount handled in the column is extremely small. In the solid state, on the other hand, atoms are not free to move around and the process would not work.

The second fact is that the great height of the column means more than a great practical inconvenience, because for a very tall column, the time for which one has to leave the material there until it comes into equilibrium, i.e. until the light atoms have migrated to the top and the heavier ones to the bottom, becomes very large. Actually, such a column could only be skimmed after some thousand years, and this, clearly, ruins the whole idea.

However, the picture is changed if we improve on the force of gravity as provided by nature and produce 'artificial gravity', as is done in a centrifuge. It is well known that the process of separating cream from milk can be made both more rapid and more efficient by using a centrifuge. The centrifugal force in such a centrifuge takes the place of gravity, but can be much more intense, and it would seem that a plant for separating the isotopes of uranium by centrifuging is not an impossibility. In fact, such a plant was under very serious discussion in the American project. Like all the other methods we shall talk about, it is not an easy task, because of the large number of high-speed centrifuges required for the job; these are very delicate pieces of machinery and need precision methods for their construction.

Even with the fastest practical speeds, it would not be possible to produce pure 235 in a single operation of a centrifuge, but it is possible to produce a considerable enrichment, and several units would have to be combined in the cascade scheme discussed before.

4. *Diffusion and Other Methods*

Another method that was known to be suitable for the separation of isotopes relies on the diffusion of gas through porous membranes. The reasoning behind this is as follows: It is well known that the atoms or molecules of a gas are moving about at speeds which are greater the higher the temperature, and, in fact, heat is just the effect of this fast motion of molecules. At any given temperature the speed with which the molecules move depends on their weight. The speed varies inversely as the square root of the mass, so that if one molecule weighs four times as much as another its speed, at the same temperature, will only be one-half that of the lighter molecule. This means that if gas is allowed to escape into an empty space, or a space where the gas pressure is lower, the lighter molecules will tend to run faster than the heavier ones and to get ahead. Now this does not mean that if we discharge, say, a storage tank of compressed air through a pipe, more nitrogen will escape than oxygen. Here, in their passage from the tank, molecules have frequent opportunity to collide with each other, and hence the oxygen molecules, which tend to be a little more sluggish, will be hustled along by the nitrogen and this, in turn, will delay the progress of the faster nitrogen atoms. The situation is similar to a dense crowd of people walking through a passage, where everyone will make progress at the same rate even though some people may want to walk slowly and others may be in a hurry.

The high natural speed of the lighter molecules can make itself felt only in conditions in which the progress of each individual molecule depends only on that molecule itself and is not influenced by collision with the others. This is the case, for example, if gas 'diffuses' or seeps through porous material such as clay, in which it has to pass through a large number of very fine pores; the point being that each gas molecule collides more often with the solid material than with other molecules. This will delay its progress very much, and the rate of gas flow is, of course, much less than it would be through bigger openings, but these obstacles are independent of the presence of the other molecules and there is, therefore, much less tendency for the faster molecules to speed up the slower ones and vice versa, and each molecule will move at a rate that depends on its own natural speed.

This method had been successfully applied by G. Hertz to the separation of isotopes of the rare gas neon, in a laboratory apparatus which gave a few litres of gas in a run of several hours. Hertz used unglazed porcelain tubes as the porous membranes, and he had again to use the cascade arrangement. The isotopes of neon have atomic weights of 20, 21 and 22. In other words, the lightest and the heaviest differ by 10 per cent in weight and their velocities at a certain temperature will differ by 5 per cent. Hence, in the most favourable case, where we have made the pores in the membrane so small that the collisions between gas molecules do not matter at all, the rates at which the molecules diffuse through the membrane differ by 5 per cent. In other words, if we start with a mixture containing say 10 per cent of the light isotopes, the gas seeping through the membrane will have been enriched by 5 per cent of the original number of light molecules and will contain 10.5 per cent of the light isotopes. If this gas is passed on to the next stage of the cascade, the light fraction obtained from that next stage might have a concentration of 11 per cent, and so on. It is seen that even in this case a large number of steps are required before we have practically purified the lighter isotope.

In the case of uranium the problem is more difficult because the weights differ only by roughly 1 per cent and, hence, the maximum increase in the concentration in each stage would, in most favourable conditions, only be approximately 0.5 per cent. In other words, for ideal conditions the fraction of light atoms would, per stage, increase by something like a factor 1.005. Since this fraction is only 0.7 per cent to start with, we see again what a formidable undertaking is presented by our problem. Moreover, uranium itself is not a gas ordinarily but a metal, and to vaporise it would require temperatures for which no porous membranes or pumps could be found. It has, therefore, to be used in a compound, and of the compounds of uranium, only one is a vapour in conditions that are at all suitable for practical purposes. This is the hexafluoride of uranium, consisting of 6 atoms of fluorine combined with one atom of uranium. The atomic weight of this combination is 352 for the heavy

uranium and 349 for the lighter. The weight difference is, therefore, even somewhat less than 1 per cent.

The properties of this compound make it an extremely unpleasant substance to handle. It is highly corrosive and many of the materials ordinarily employed in constructing chemical apparatus would be attacked by the gas. This is bad not only because it will gradually destroy any apparatus in which such materials are used, but also because in the reaction the gas itself decomposes, and in place of the volatile uranium compound we are left with a solid deposit on the wall which will be lost from the process. Since, in the very many stages of a separation plant, the gas has to circulate for a very long time before it eventually finds its way into one of the end stages, one cannot afford to lose even a small fraction of the gas on the way; otherwise there would be no product left at all when one finally got to the end. In addition, such solid products may also form dust which will tend to settle in the fine pores of the membranes and make them unusable. One of the worst enemies of uranium hexafluoride is moisture, which will not only react with it and decompose it, but at the same time liberate from it fluorine in combinations such as hydrofluoric acid, HF, which is an even more highly corrosive substance. Throughout all the stages of a separation plant, the gas must, therefore, be extremely carefully protected from contact with ordinary atmospheric air, which is always moist.

In order to collect the gas that has passed through the membranes and compress it again to make it ready for passing through the membranes of the next stage, pumps are required, and these again must be of a very unusual design, since the construction materials ordinarily used for pumps, and, for example, the oil and grease normally used to lubricate them and prevent leakage, would be attacked by the gas very rapidly.

The size of the pumps required depends very much on the perfection of the membranes one uses. The connection is as follows: We have seen previously that it is necessary that the pores be so small that, in their irregular motion through the pores, molecules should run into a pore wall more often than they run into other molecules. Now, collisions between molecules depend on the density of the gas. If the gas is denser, molecules collide more frequently, and hence for each kind of membrane there is a greatest gas density or gas pressure for which they will work satisfactorily. If we make a better membrane with smaller pores, we can afford also more collisions between molecules and, therefore, a higher gas pressure. Now the size of a pump does not depend much on the actual mass of gas it handles, but chiefly on its volume. If we have to work at lower pressures, the same amount of gas will occupy a larger volume and therefore need larger pumps.

To summarise, we can see from this description that, in principle, the process of separating isotopes by diffusion is simple enough, but that the practical problem involved in finding membrane materials, construction materials, lubricants and seals that would stand exposure to the corrosive gas, in designing pumps, in building a plant containing all these pumps, and keeping it completely protected from external air, and in controlling the flow of gas through all the many stages of the cascade scheme, represents an enormous undertaking.

It is not at present possible to describe the many ingenious inventions that were made in the course of overcoming all these difficulties, but it is by now common knowledge that the difficulties were overcome by the co-operation of large teams of scientists and engineers, and that a plant working along these lines is in operation.

There exist other methods which depend on the different speeds of isotopes of different weight; one of them being a method also developed by Hertz, which uses the diffusion of gas through a stream of another gas rather than through a membrane. Another method, due to Hevesy, uses the fact that if you evaporate a liquid while keeping the space above the liquid evacuated, the lighter components of the liquid

will evaporate more quickly, since there again the motion of the vapour molecules is more rapid. These and many other methods were discussed and discarded as less suitable to the problem in hand than the diffusion through membranes.

One method that came to mind immediately when the problem first arose was that of thermal diffusion of a gas. This term is applied to a peculiar phenomenon that is found in most gases and consists in a tendency of lighter molecules to go to the hotter part of a tube and for the heavier ones to go to the colder end, if the two ends of the tube filled with gas are kept at different temperatures. The particular attraction about this scheme is that Clusius and his collaborators had invented a very neat trick by means of which one could avoid the use of a large number of separation stages in a cascade arrangement and could effectively have a large number of stages in a single tube. The trick works in the following way. Imagine two vertical walls close together – one hot, the other cold. Then, because of the thermal diffusion effect mentioned, the gas near the hot wall will be slightly enriched in the light isotope. At the same time, because it is hotter, this gas is at a lower density and tends to float up, whereas the colder gas tends to sink down. The result is, therefore, a circulation of the gas up the hot wall, across the top and down the cold wall. Now, since the gas near the hot wall is slightly enriched, the upward current carries an excess of light isotope and there is a net flow of light isotope towards the top and light gas will accumulate at the top until a difference in composition has been established which, by the natural tendency of the gases to mix again, will compensate the upward flow of light gas. This arrangement is equivalent to a large number of individual stages, that number being roughly equal to the ratio of the height of the column to the distance between the walls. As the height can easily be many feet and the distance between the walls a small fraction of an inch, we see that this scheme is equivalent to a great many stages, and one need only connect a few such columns to obtain a reasonable enrichment. In practice, the scheme of Clusius does not use plane walls but concentric tubes, the inner one being heated by a flow of hot liquid or gas, the outer one being cooled.

Unfortunately, measurements of the thermal diffusion effect in uranium hexafluoride showed immediately that in this particular gas the effect happens to be extremely small. The causes for the effect are complicated and depend a great deal on the nature of the molecules and the forces between them, so it is not possible to predict beforehand whether it is going to be large or small in any particular gas. In this gas, however, it turns out to be so small that a plant built on this principle would be quite prohibitive in cost, power consumption, and size, even though it has the great advantage of simplicity and contains no moving parts.

Many people had studied the same principle as applied to liquids, and had always found that use of liquids was very much less efficient than use of gaseous compounds, the chief reason being that liquids have a higher heat conductivity, so that if a gap between a hot and a cold wall is filled with liquid, much more heat is supplied on the hot side and more taken away by cooling on the other side to maintain the same difference in temperature. It was, therefore, thought that the same would be true in the case of uranium hexafluoride, but experiments carried out by Abelson gave the surprising result that, while the thermal diffusion coefficient of gaseous uranium hexafluoride was extremely small, that of the liquid happens to be rather large, and that using liquid hexafluoride it was not impossible to build a plant of reasonable dimensions. Even so, it would have been impossible to rely on such a plant entirely for the production of pure uranium-235. Even for a moderate enrichment, the plant would consume very large amounts of heat, for example in the form of steam. There was, however, during the completion of the separation plant at Oak Ridge, Tennessee, a period when a large capacity for steam production was available while the plant that was to use it had not been completed. It was then decided to erect a thermal diffusion

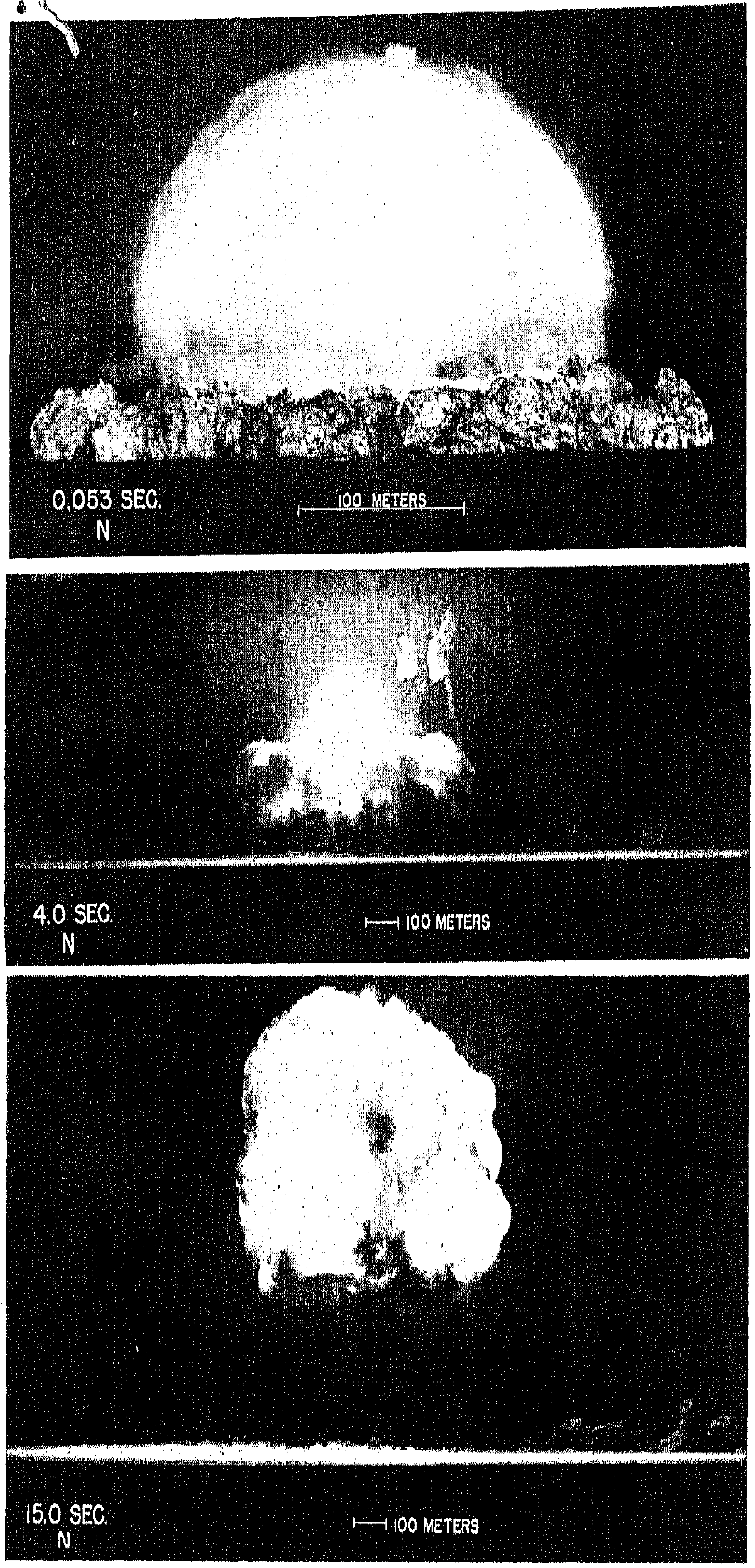


Plate 1: Three pictures taken by cine camera of the test explosion made in the desert in New Mexico on July 16th, 1945. See 'The Physics of the Bomb' by P. Morrison. (*Copyright in U.S.A. by Julian Mack for the Assn. of Los Alamos Scientists.*)

ATOMIC ENERGY PLANTS

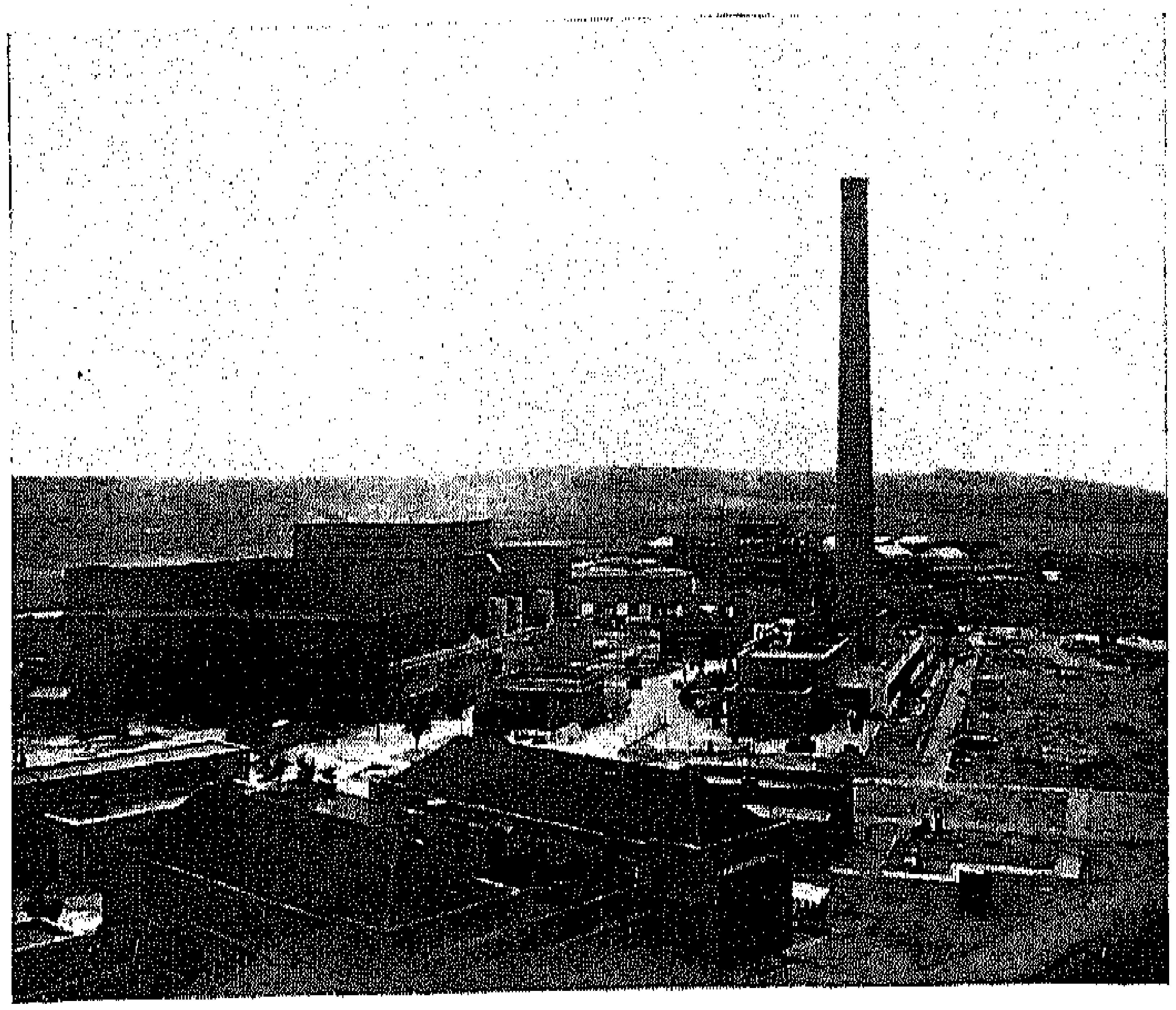


Plate 2: Great Britain, Harwell. (*Crown copyright reserved.*)

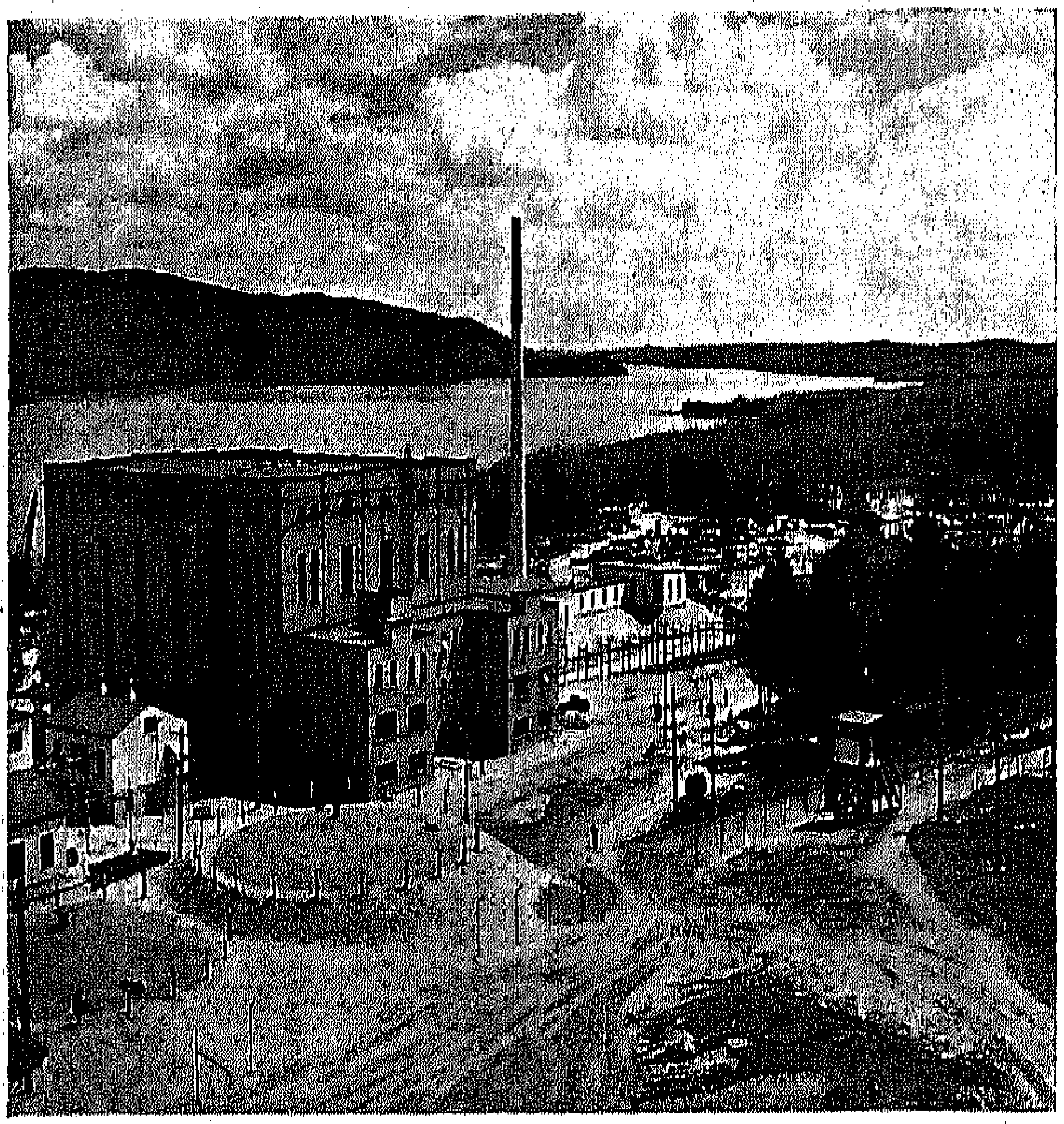


Plate 3: Canada, Chalk River. (*National Film Board.*)

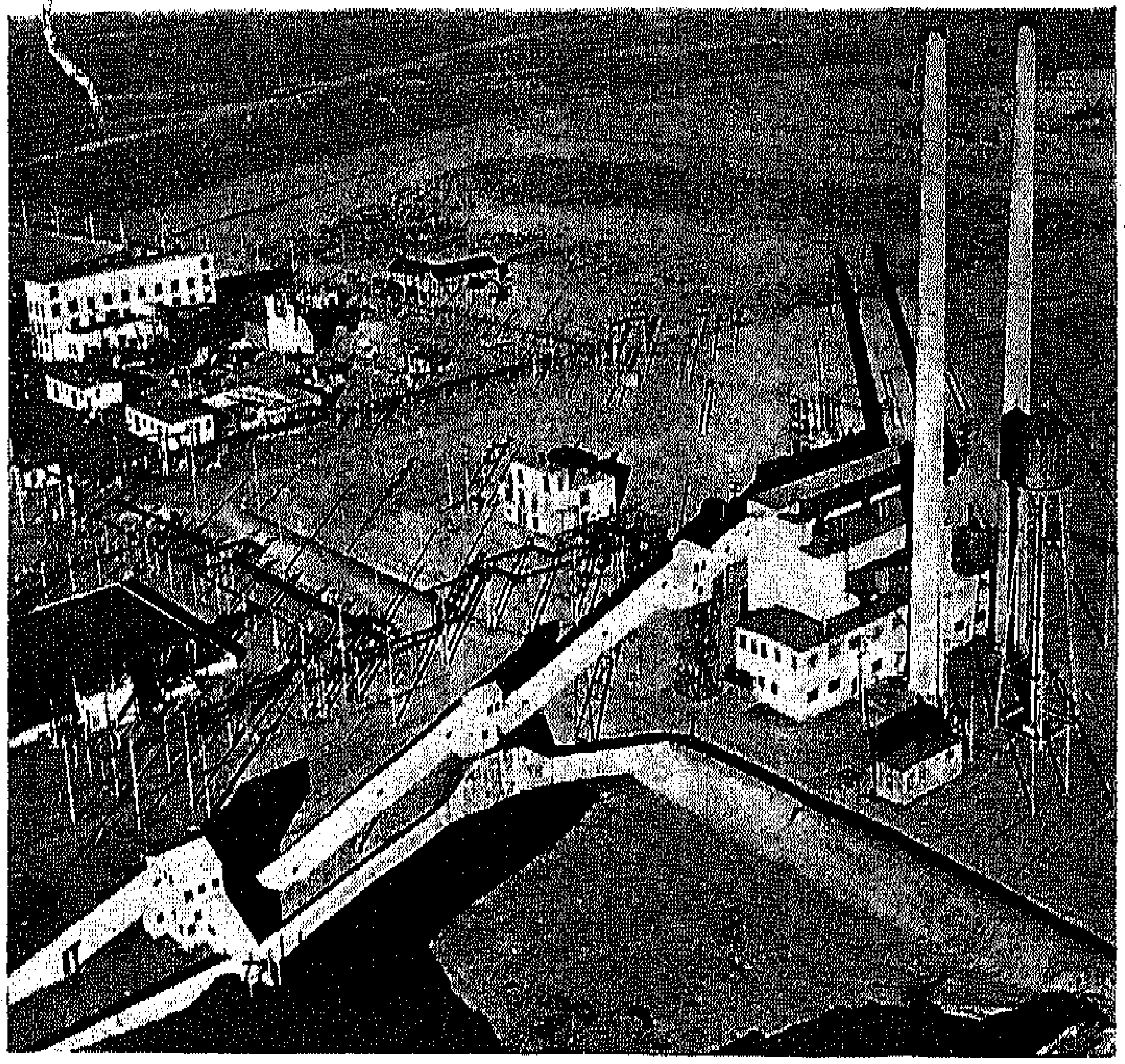


Plate 4: U.S.A., Hanford Engineer Works. (*Acme Photo.*)

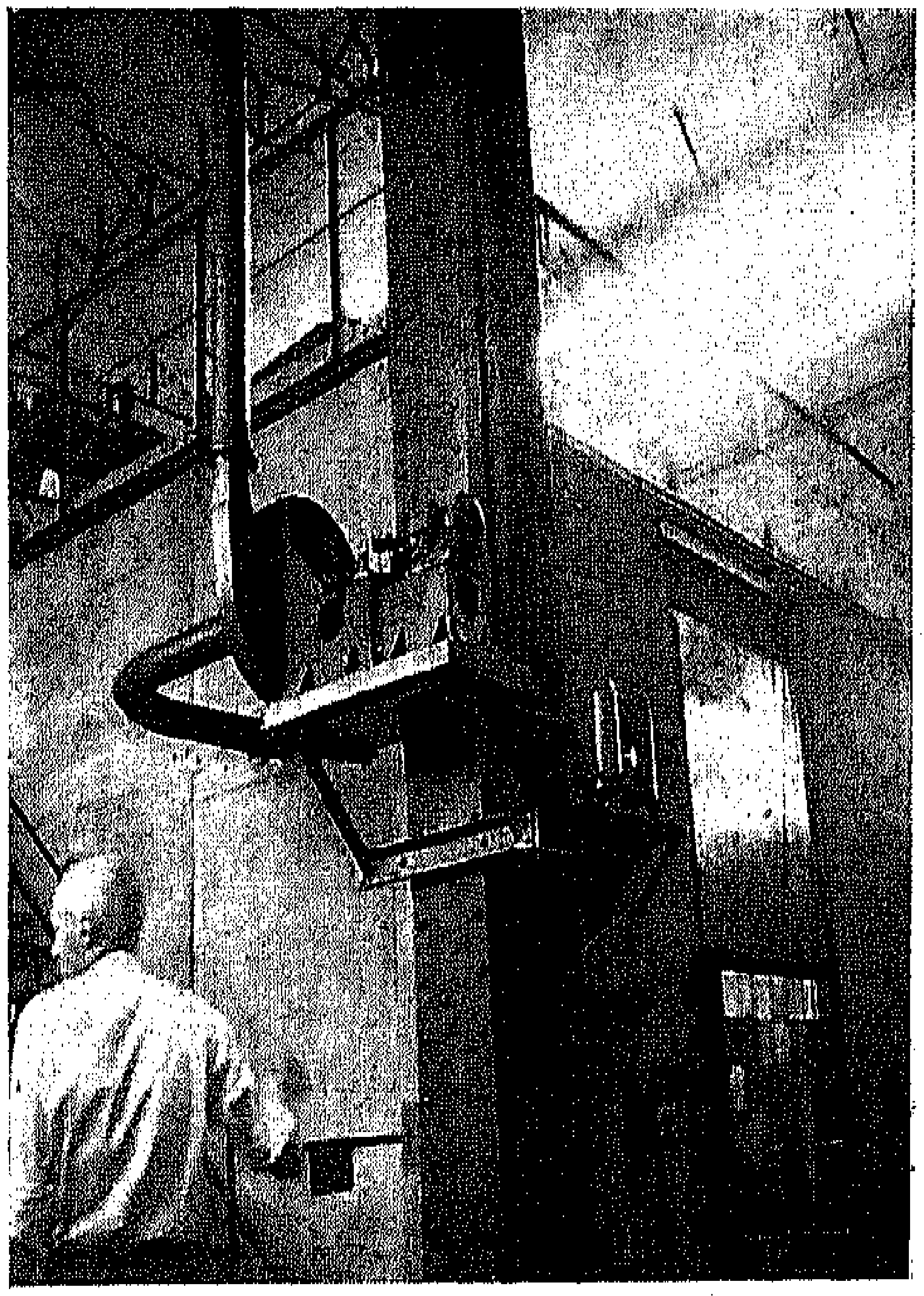


Plate 5: France, a view of the nuclear pile (ZOË)
at Fort Chatillon, near Paris.
(*Compare with plate* 7.)

GRAPHITE LOW ENERGY EXPERIMENTAL PILE

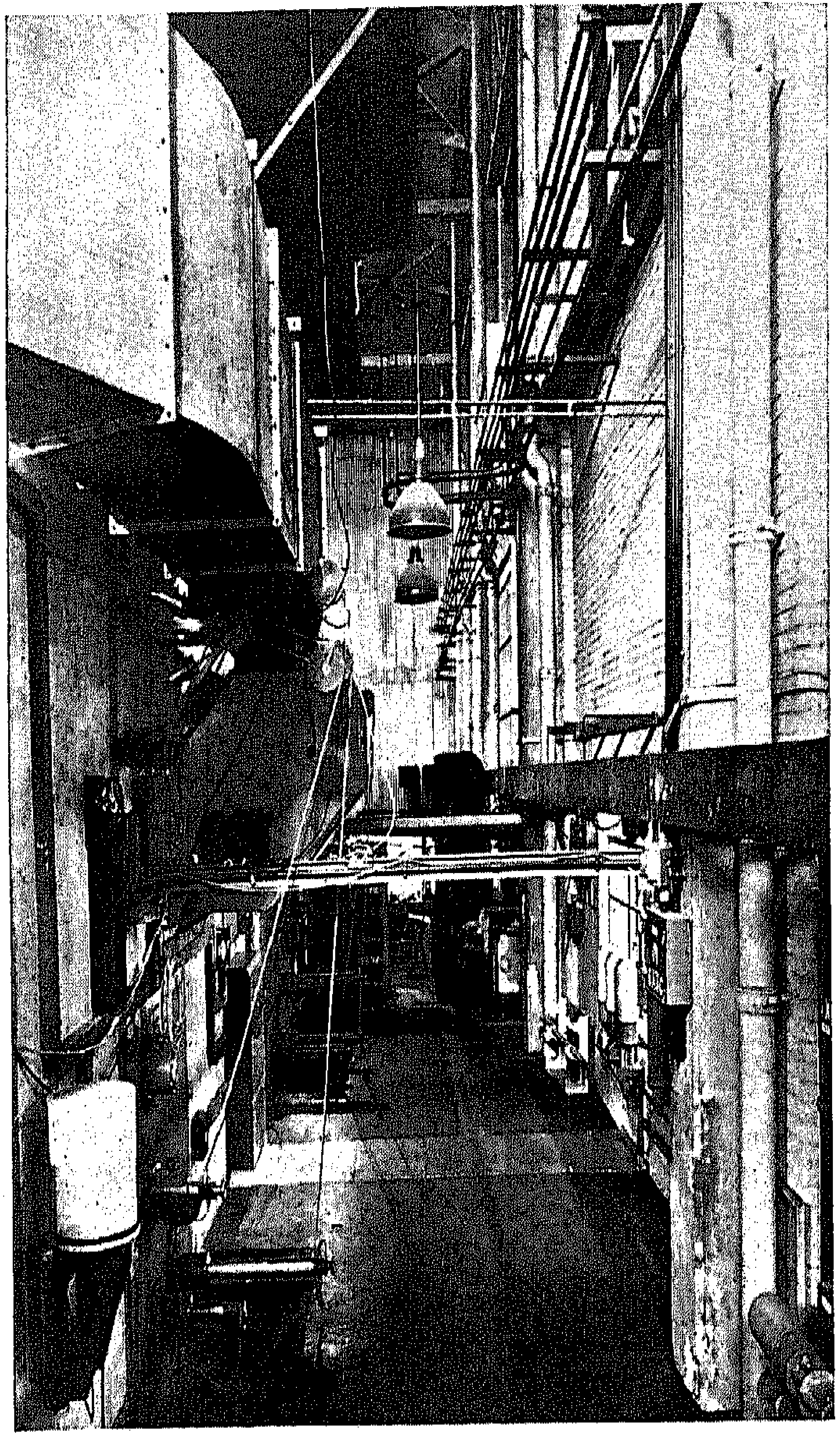


Plate 6: The control face of GLEEP is on the left: along the bottom of the wall are boron trifluoride chambers which measure the neutron intensity in the pile, and control the power level at which the pile is operated by moving the cadmium rod plungers. See 'Nuclear Reactors' by Sir John Cockcroft. (*Crown copyright reserved.*)

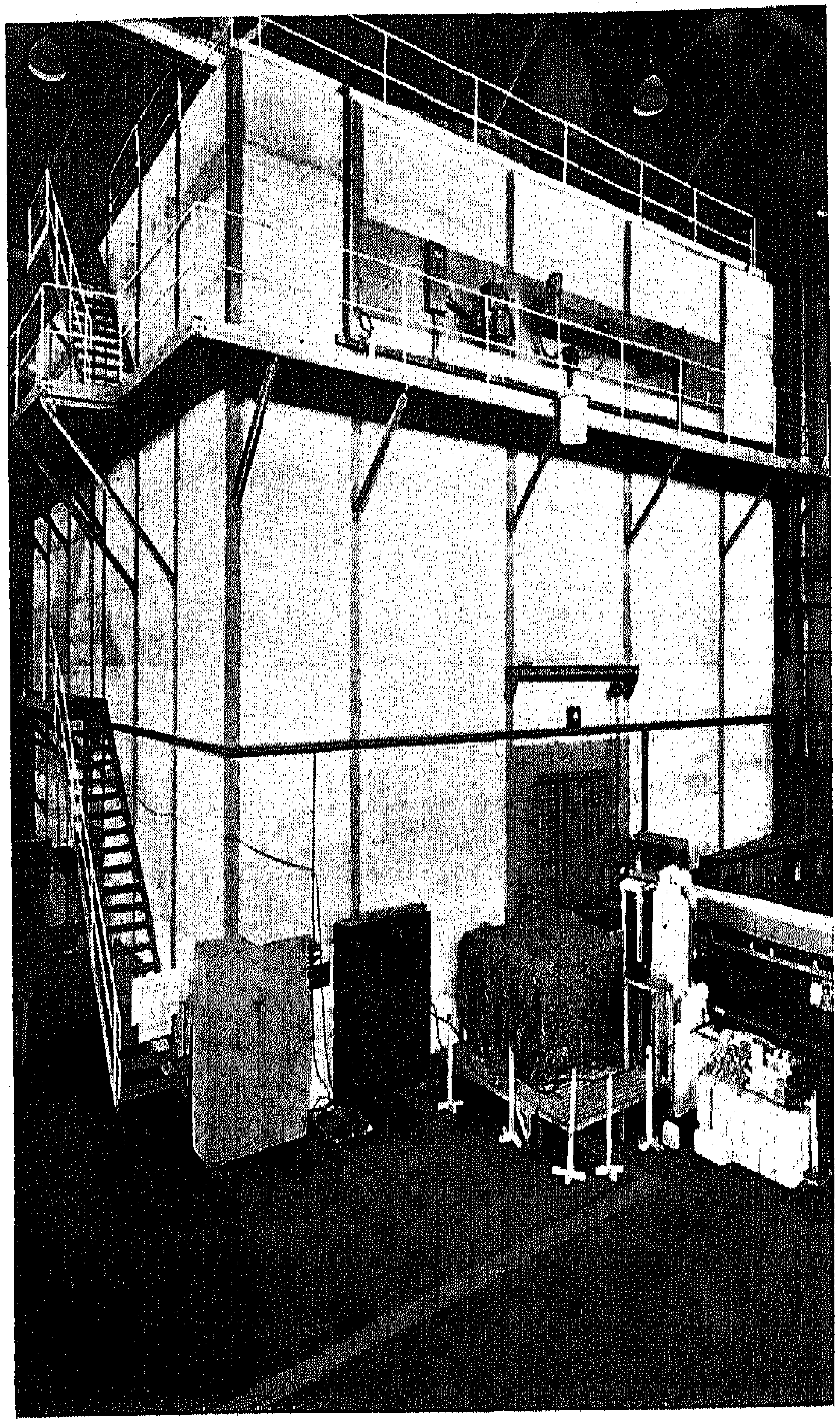


Plate 7: Another view of GLEEP: the right-hand face has a square screen of lead blocks which covers a graphite column through which issue slow or 'thermal' neutrons for experimental work. There are also holes through which specimens can be put into the pile to make radio-isotopes. (*Crown copyright reserved.*)

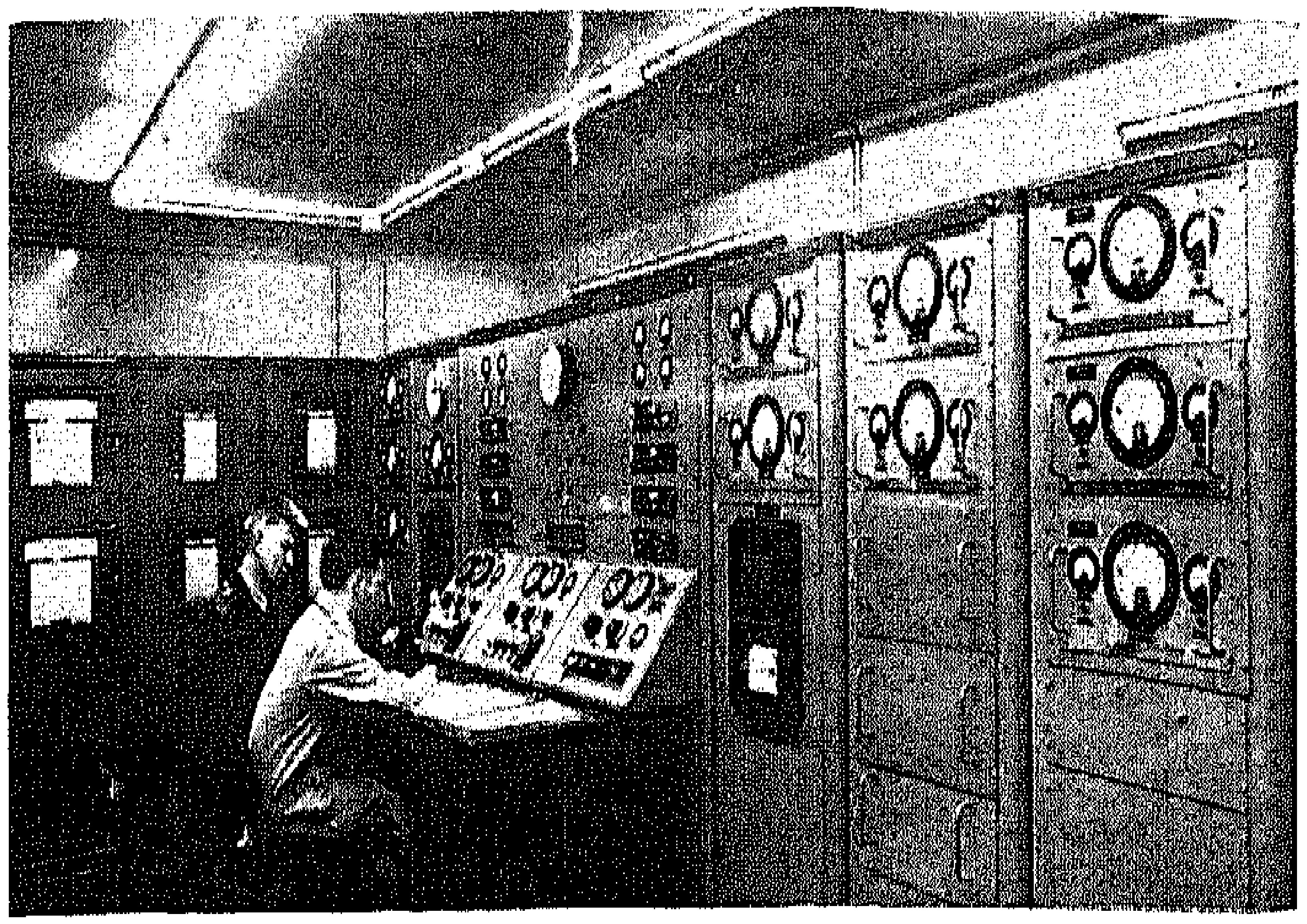


Plate 8: GLEEP's control room. (*Crown copyright reserved.*)

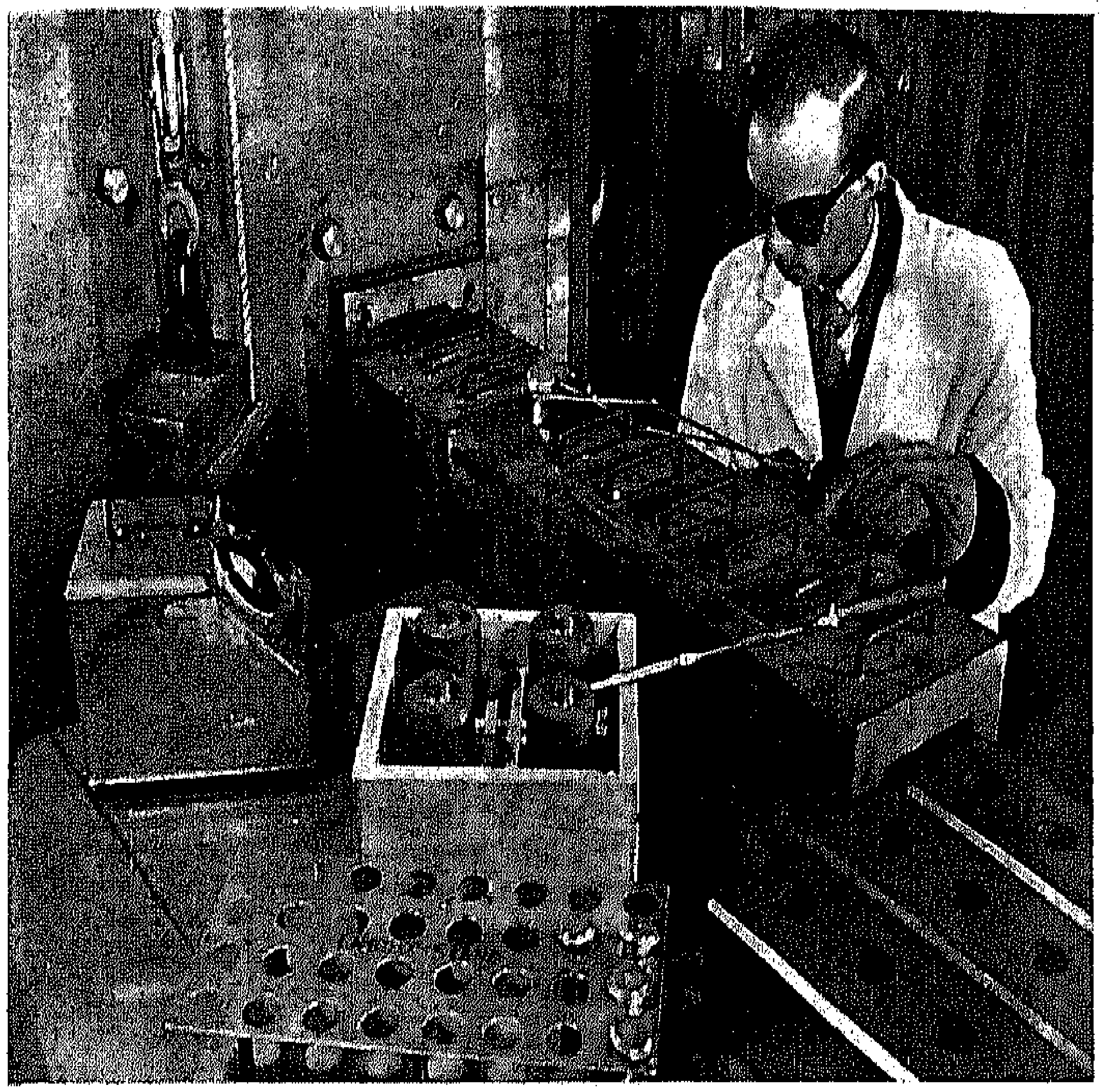


Plate 9: A close-up of the lead block area mentioned in Plate 7, and now seen in the background. Specimens are placed in aluminium tubes (one is held up in the tongs), stood up in long graphite blocks (bottom right of picture) and slid into the pile. When they are sufficiently radioactive they are withdrawn inside a lead tunnel shield (the long block through which the operator is lifting a specimen), and transferred to the lead pots (centre) for transport. Note the operator's protective gloves and goggles and the instrument for measuring the radiation in his vicinity (left, on work bench). (*Crown copyright reserved.*)

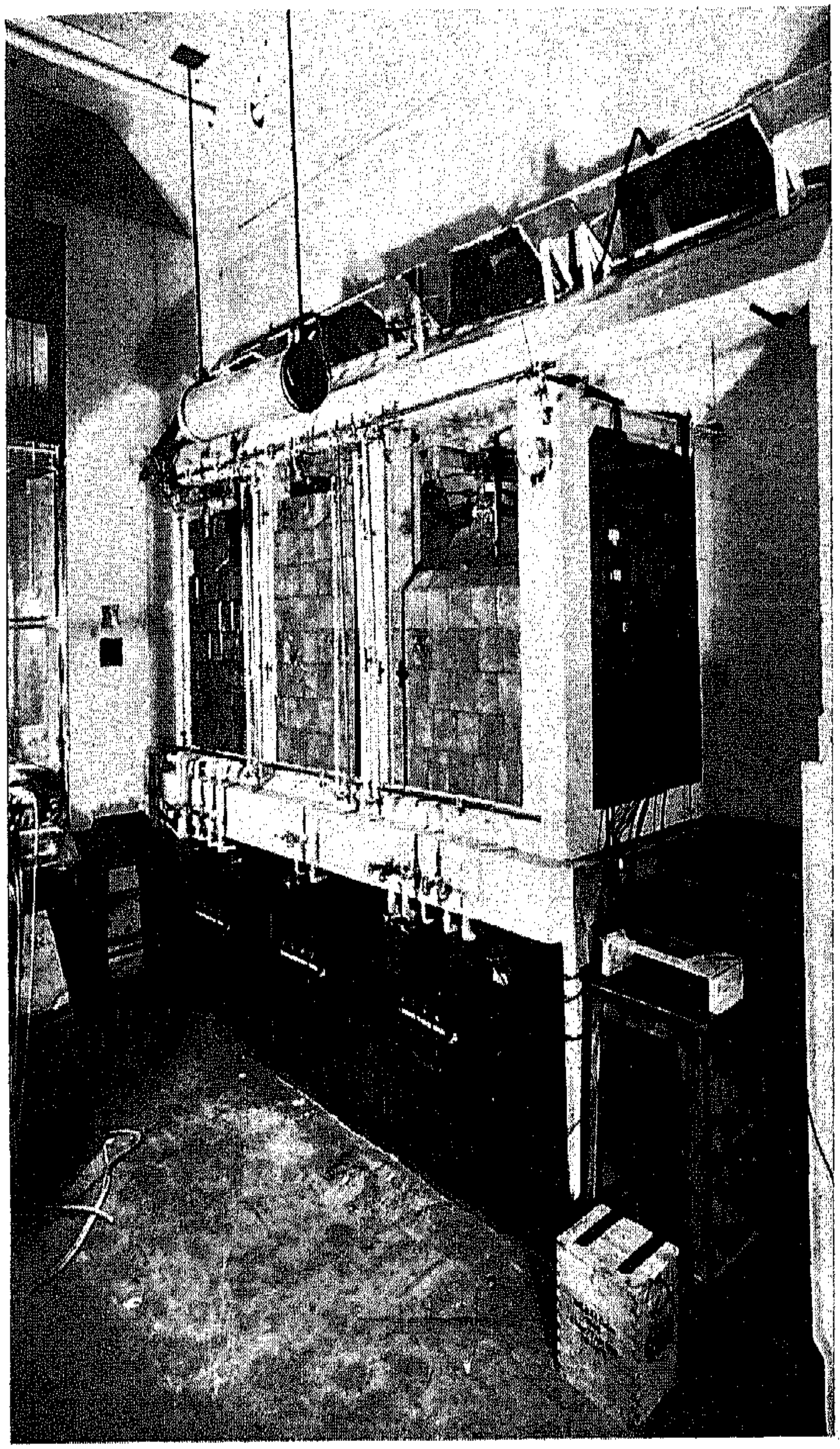


Plate 10: A radiochemical laboratory at Harwell. Experiments are carried out behind the protective lead walls, which can be built up to any desired size with interlocking blocks. All operations are controlled remotely, and observed by means of the mirrors above the apparatus. (*Crown copyright reserved.*)

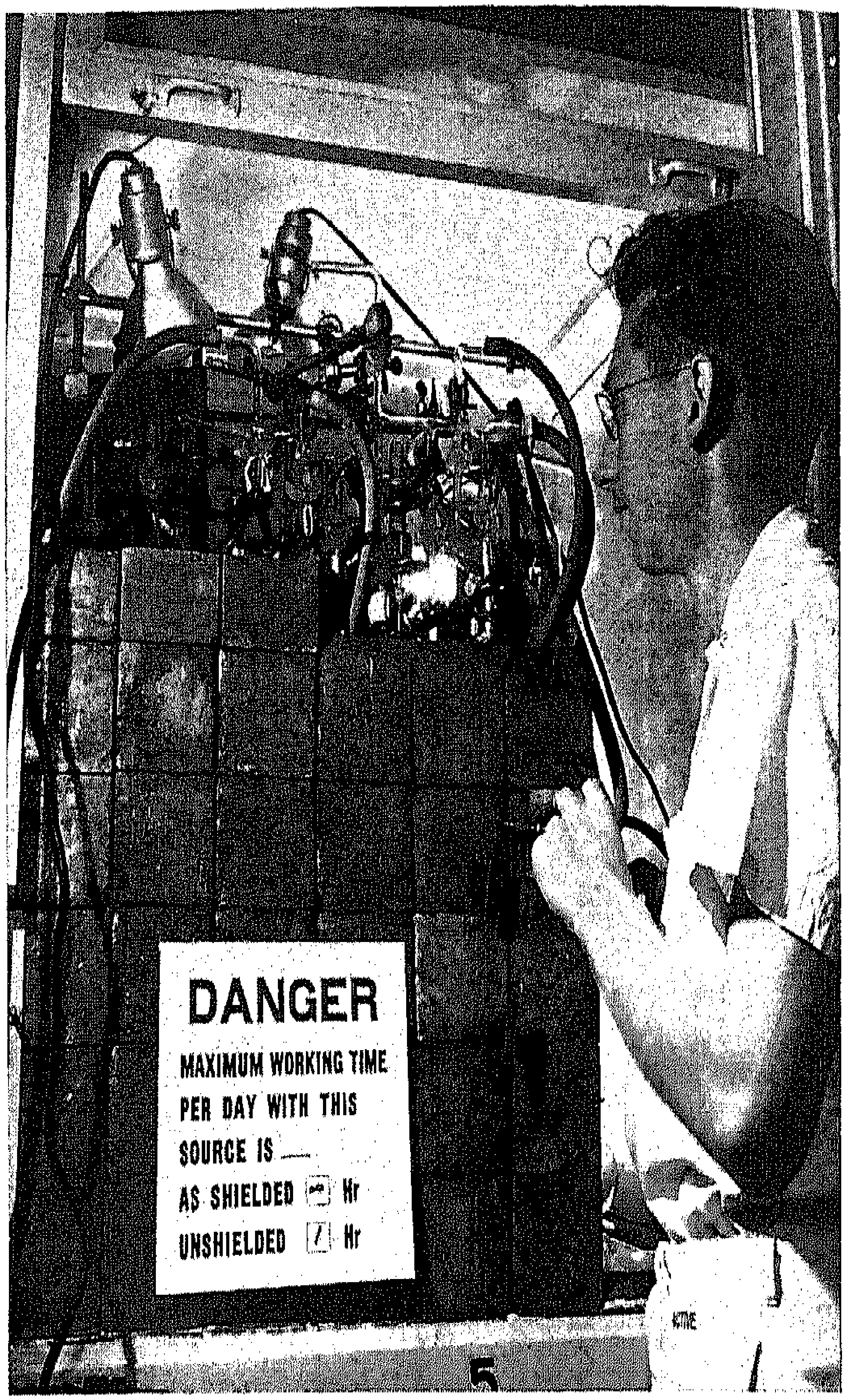


Plate 11: A radiochemical experiment behind a shielding of thick lead bricks: purifying radioactive isotopes from fission products. (*National Film Board of Canada.*)

Plate 12:
A pistol monitor. This is typical of the portable health instruments used in work with radioactive substances. It measures the intensity of beta or gamma radiation in the neighbourhood of its 'muzzle'. See 'A Note on Health Hazards'. (*Crown copyright reserved.*)

Plate 13:
Cloud chamber picture of beta particles (fast electrons). The source is contained in the metal block visible at the bottom. Electrons are easily deflected, and hence their paths are tortuous. Some of them are seen to collide with atoms and produce secondary electrons visible as little 'spurs'. (*Courtesy of the Cavendish Laboratory.*)

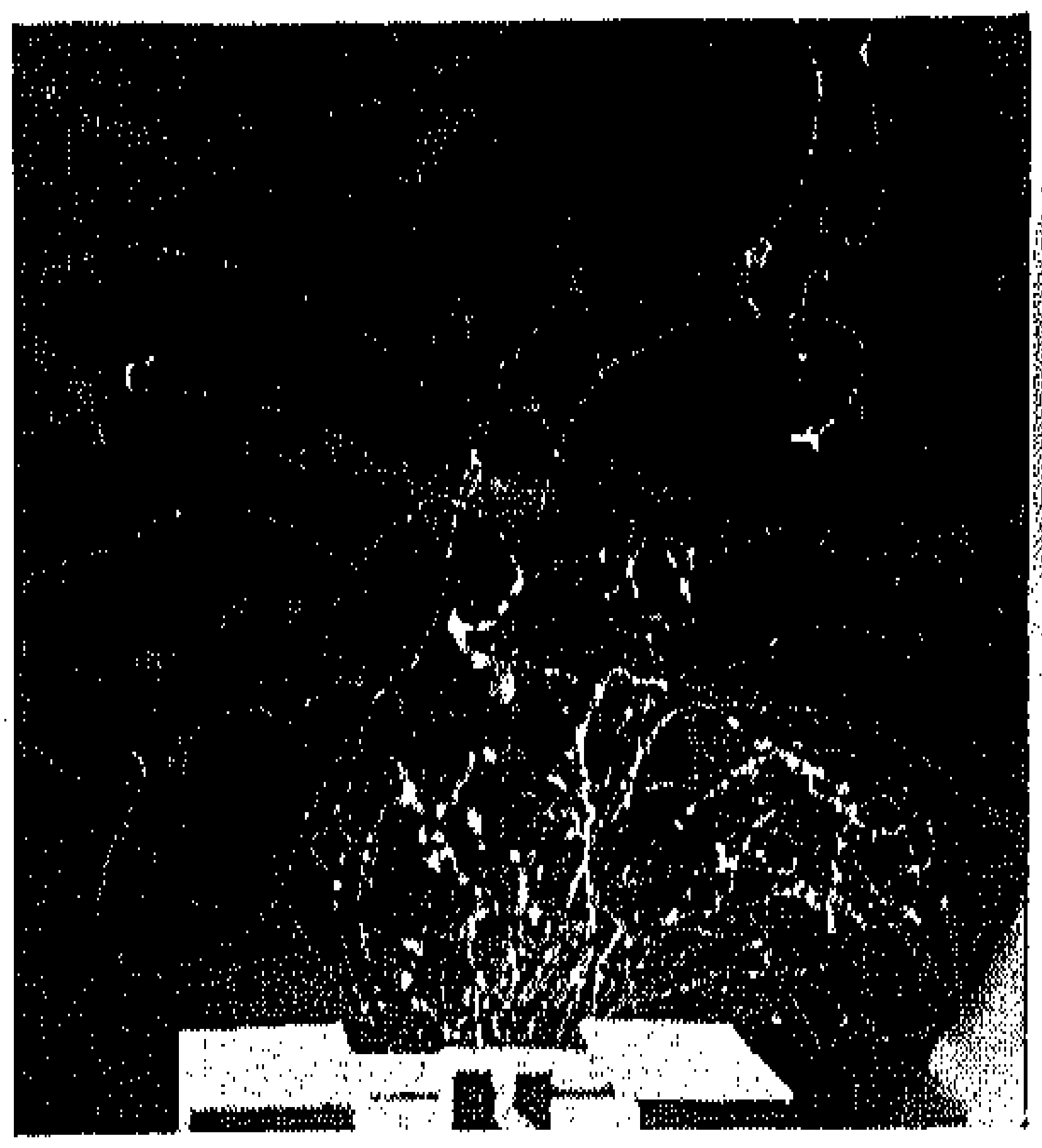
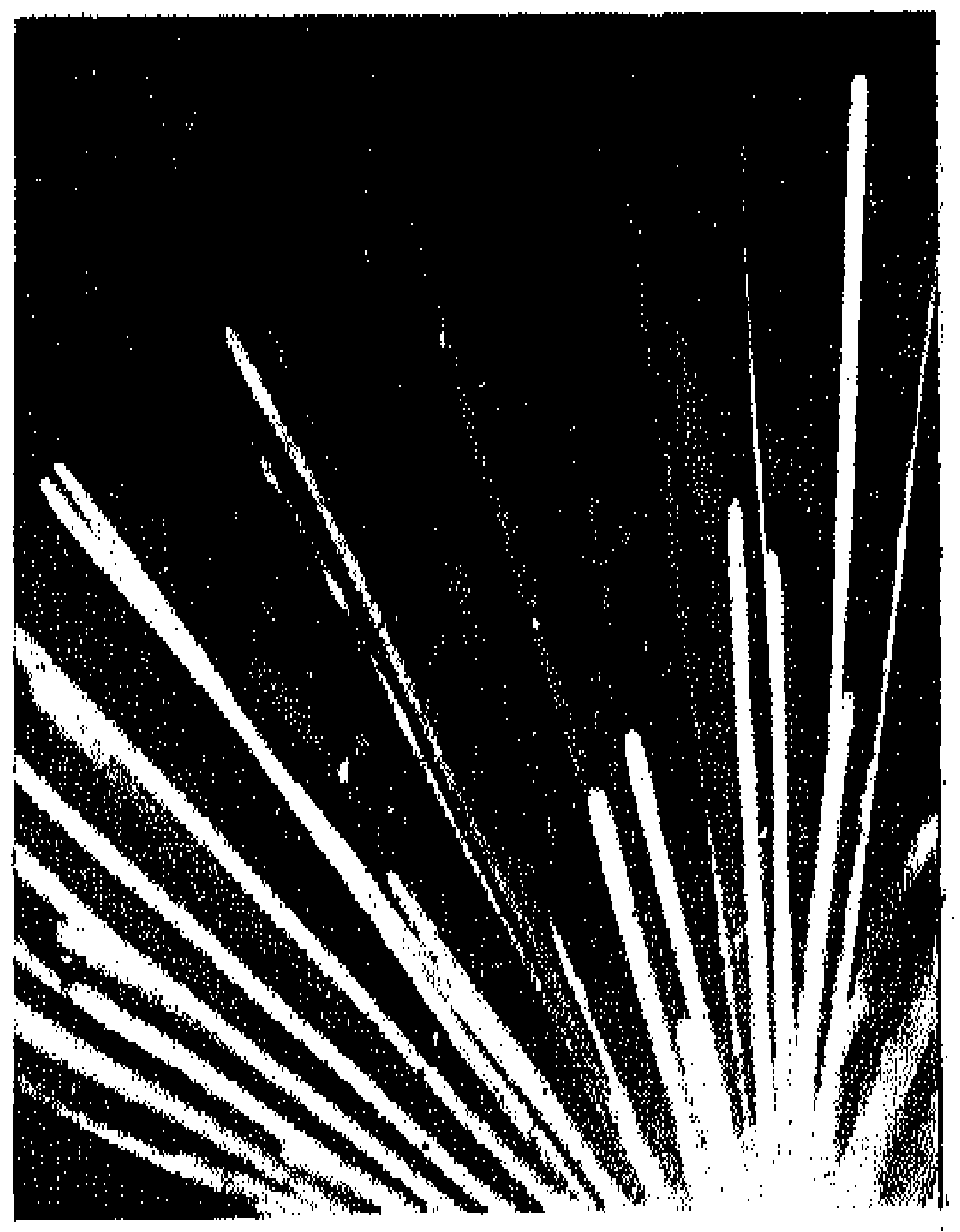


Plate 14:
Cloud chamber picture of alpha particles from a source of Thorium C. The alpha particles are of two different energies, as shown by two different ranges. The preparation was not quite clean, so some of the alpha particle tracks are shortened. The thin tracks are due to particles which entered late, with not enough water vapour left. (*Courtesy of the Cavendish Laboratory.*)



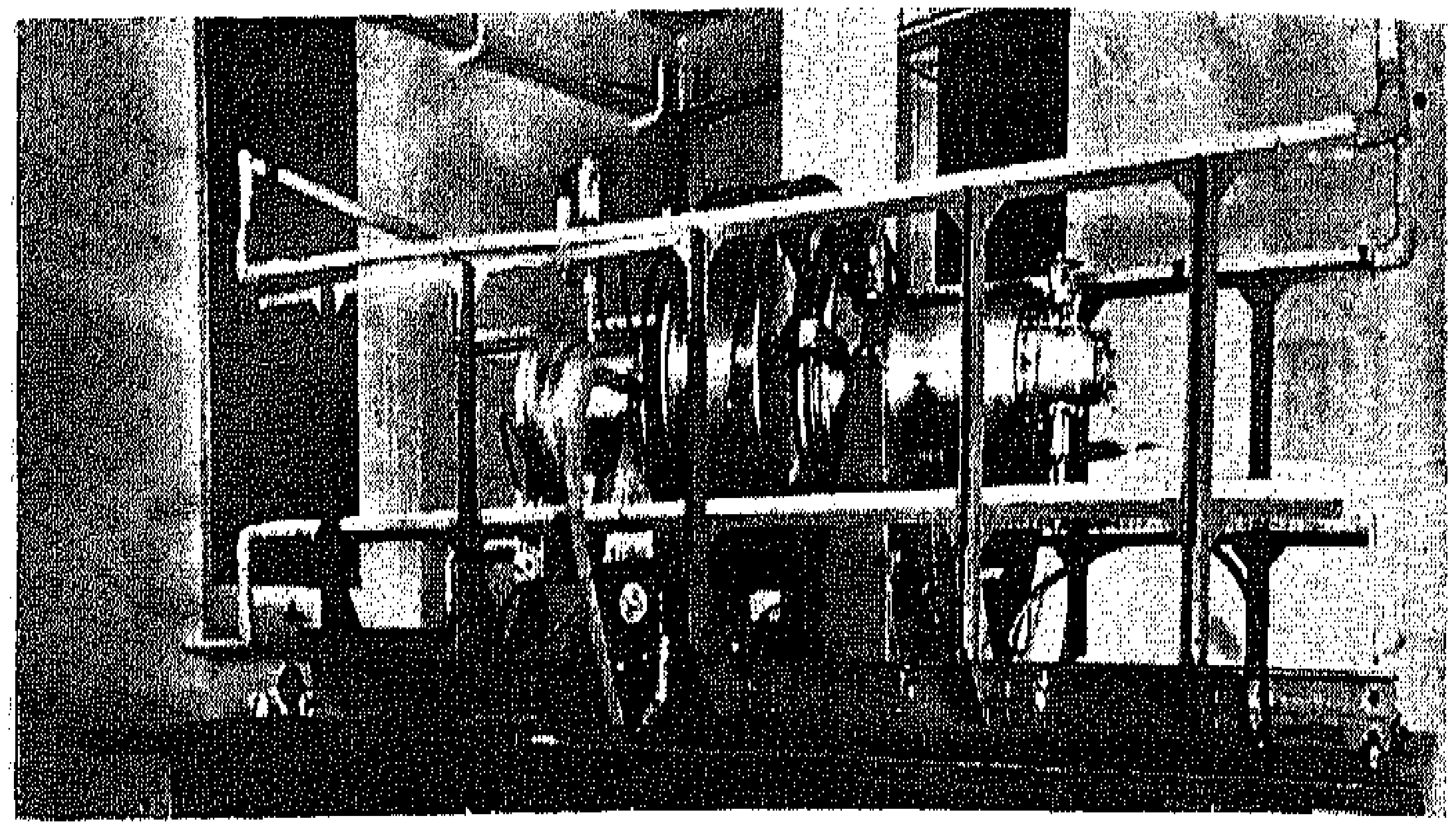


Plate 15: The Harwell Beta-Spectrometer serves to separate electrons of different energy. The source of electrons (the beta-active preparation) is placed at one end of the big evacuated aluminium tube. Some of the electrons which it emits in all directions pass through the magnetic field which is produced by the big coil surrounding the middle of the tube. The electrons are twisted together by the field and those which have the right energy are focussed on a Geiger-Müller counter at the other end of the tube and are counted. By varying the current in the coil, one can successively focus electrons of different energies and find out how many there are for each energy value. The white horizontal bars are part of auxiliary coils for reducing the disturbance caused by the Earth's magnetic field. (*Crown copyright reserved.*)

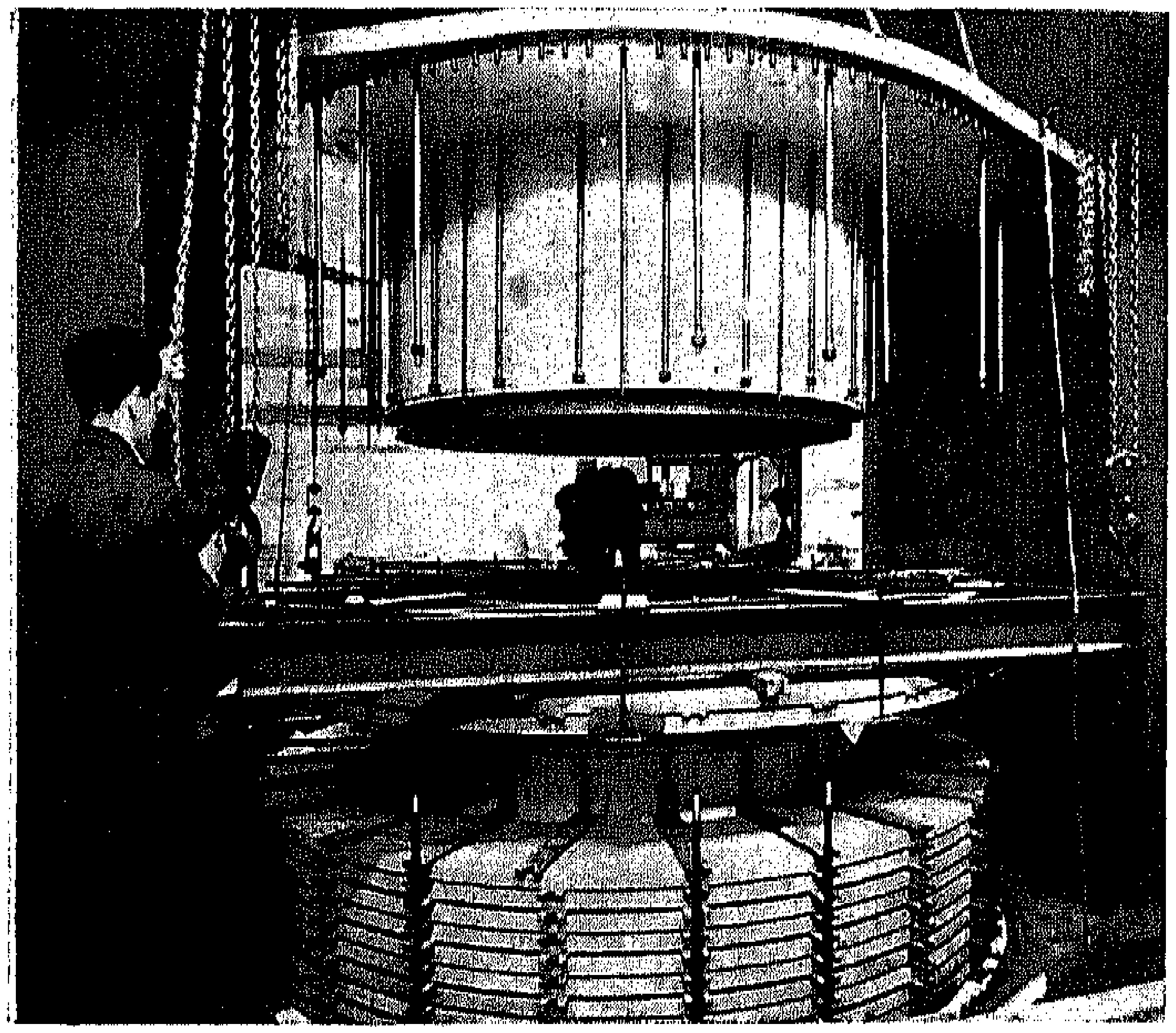


Plate 16: The Harwell cyclotron under construction. Some of the copper windings have been installed on the lower pole, but none are yet in place on the upper pole. When it is finished, the gap between the two poles (of the giant magnet) will be one foot and will hold the Dees inside which protons or deuterons will be accelerated. (*Crown copyright reserved.*)

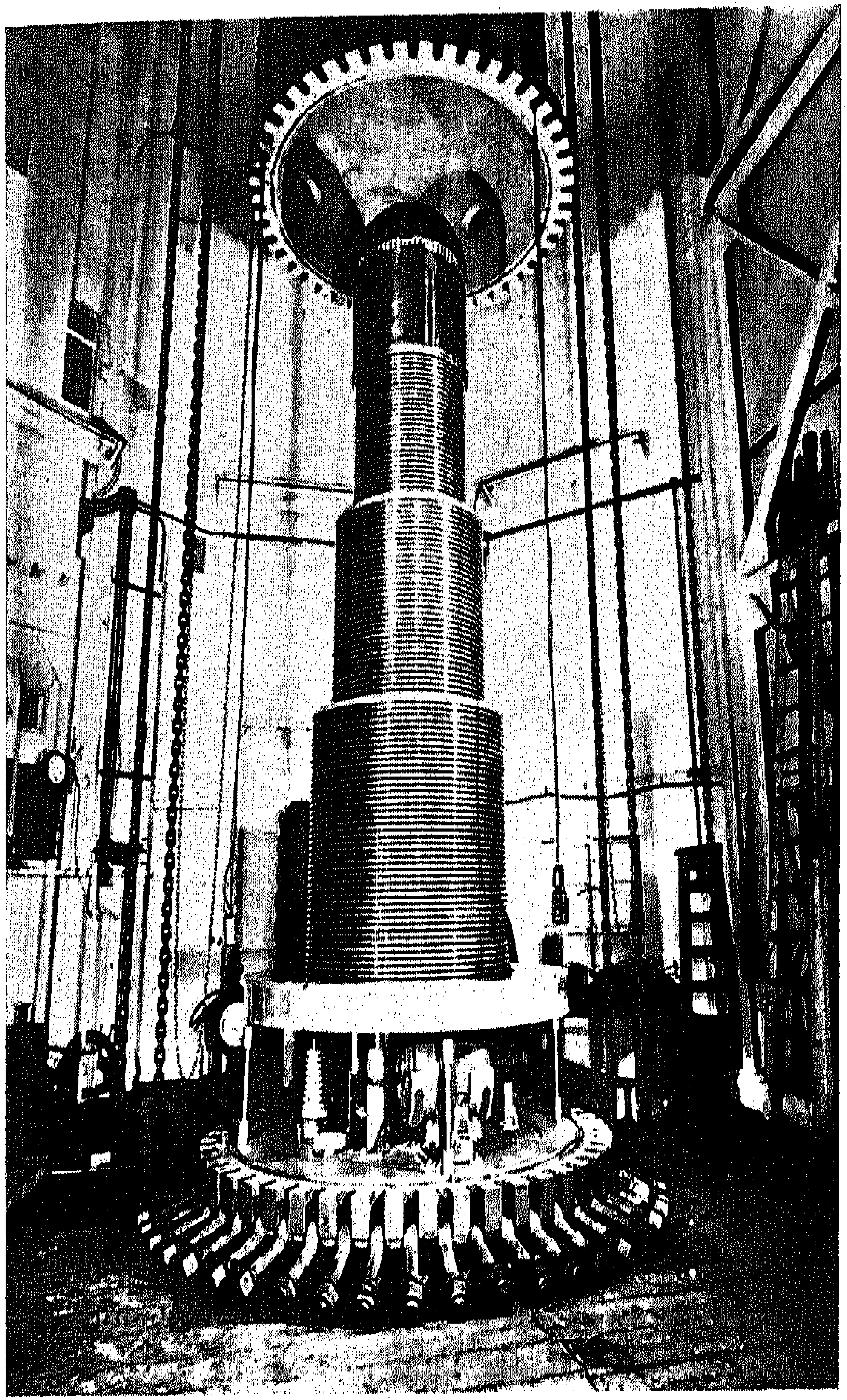


Plate 17: The Harwell Van de Graaff high voltage generator. When it is in use the boiler (the lower rim of which is seen top centre), is lowered over it, to enable the machine to work in nitrogen at high pressure. This permits higher voltages to be reached. The rounded metal knob on the top is the high-voltage terminal which becomes charged by the movement of an endless belt running inside the column and driven by the electric motor just visible underneath its base. The column itself is a pile of metal rings kept apart by thin insulators, and also contains the accelerator tube (visible at one point running down to the left of the motor). See 'The Tools of Nuclear Physics'. (*Crown copyright reserved.*)

Plate 18: This workman wears a mask and protective clothing. He is filling 100 lb. bags with uranium ore worked up from pitchblende mined at Port Radium on Great Bear Lake near the Arctic Circle. (*National Film Board.*)

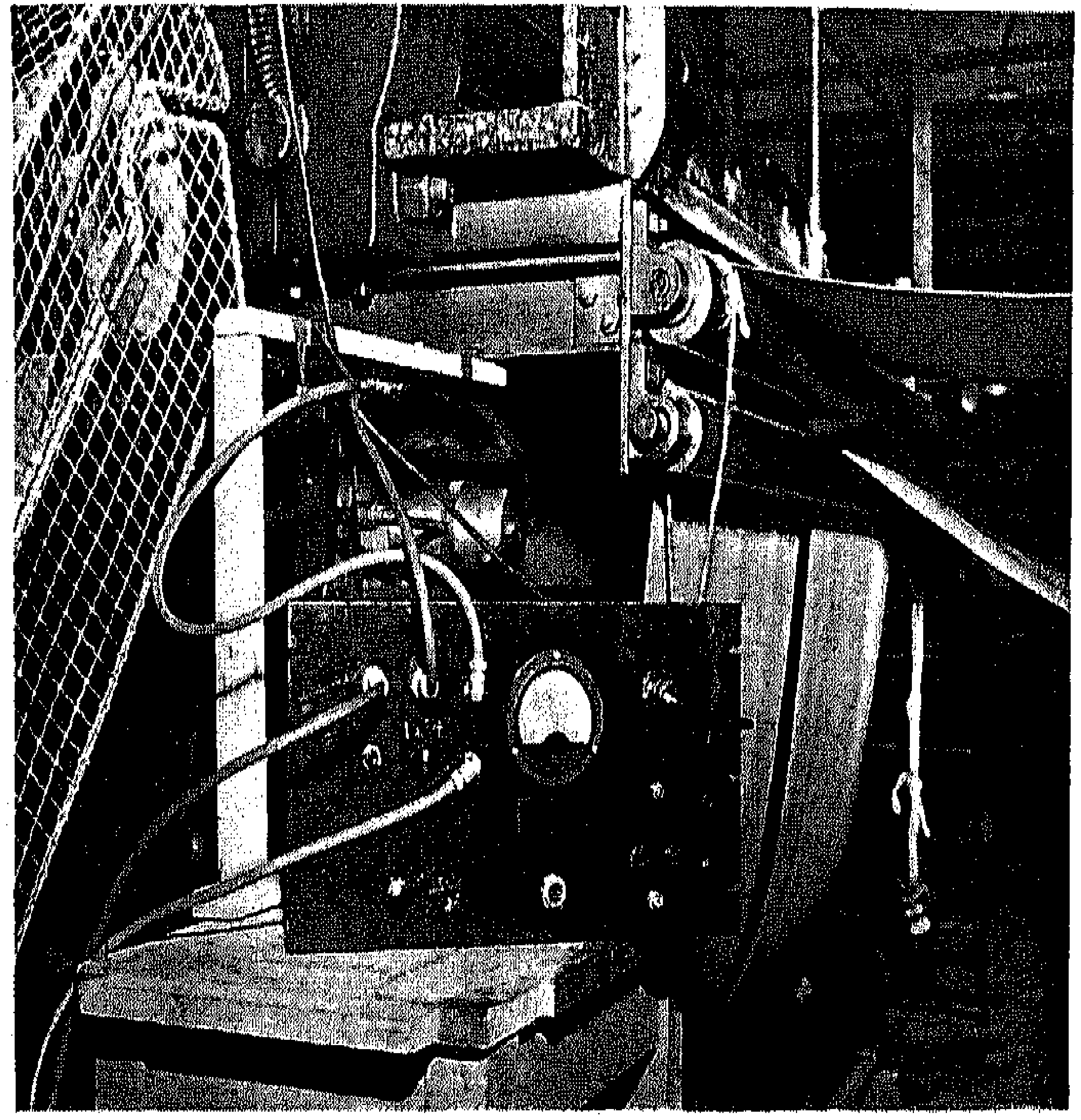


Plate 19: A Beta Gauge which records the thickness of linoleum. See 'The Use of Radioactive Isotopes in Biology and Industry'. (*Reproduced by kind permission of the Linoleum Manufacturing Company Ltd.*)

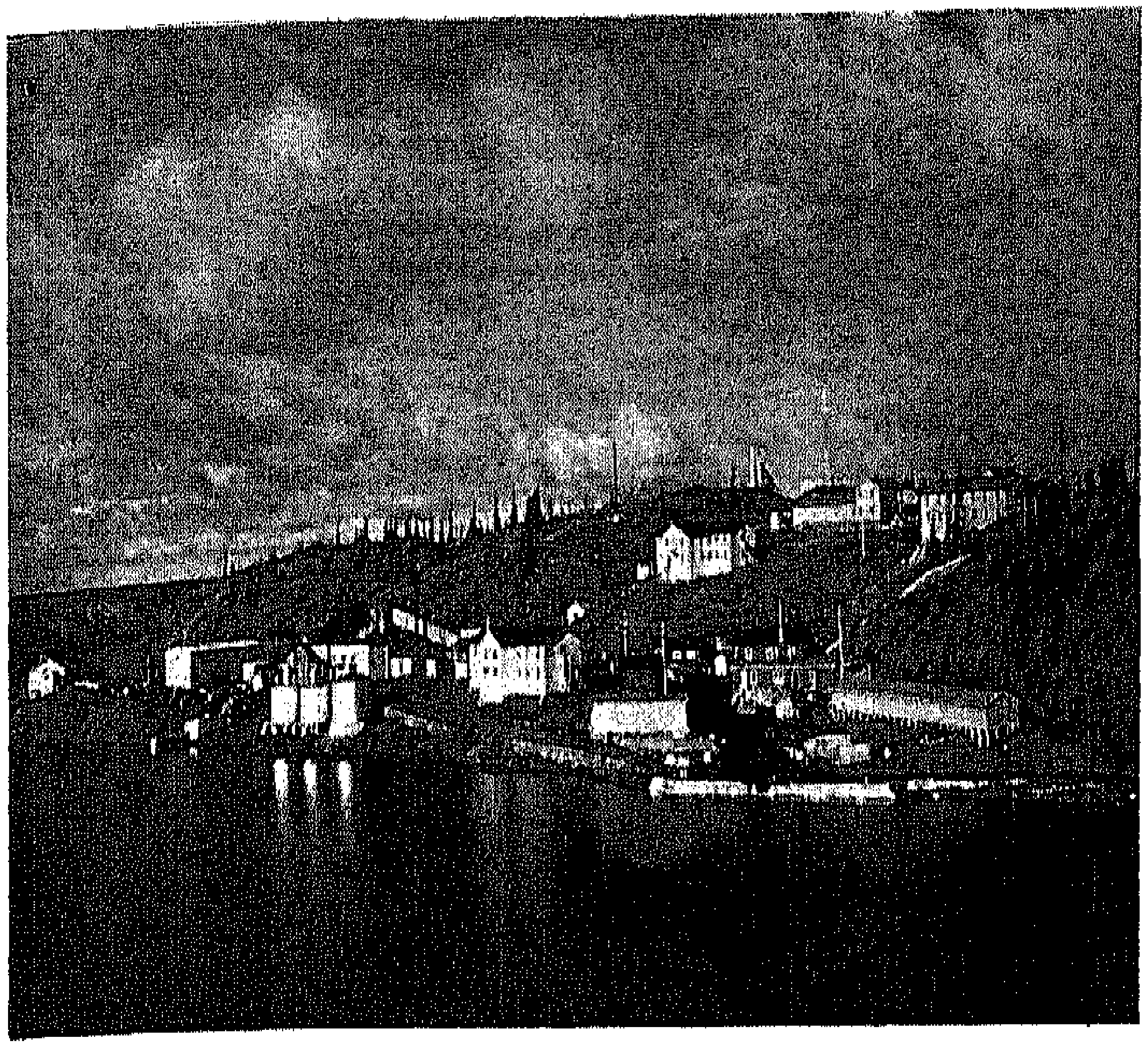


Plate 20: A view of the Eldorado Mine at Port Radium (Canada) which shows the barren wildness of the country. (*National Film Board.*)

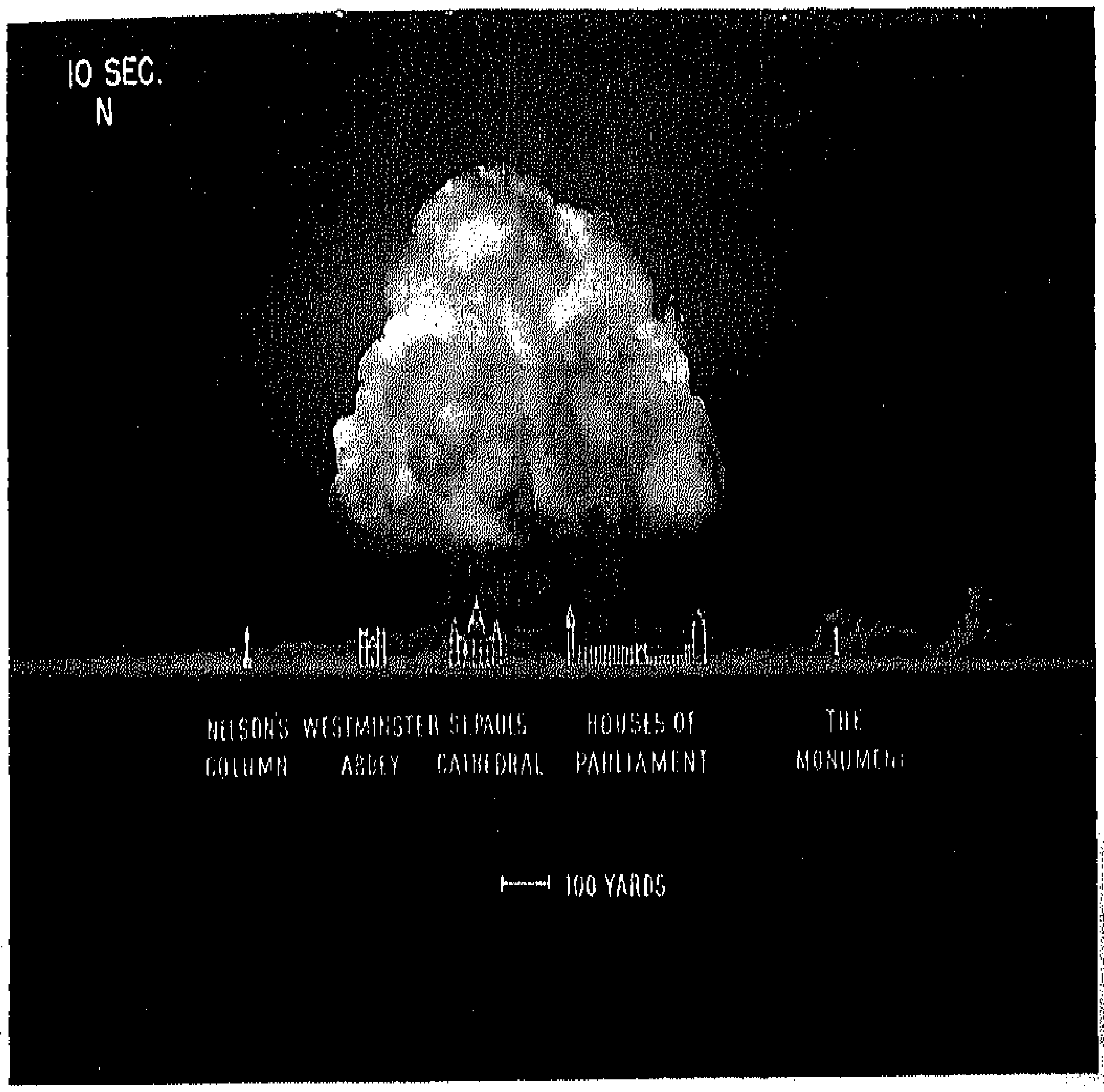
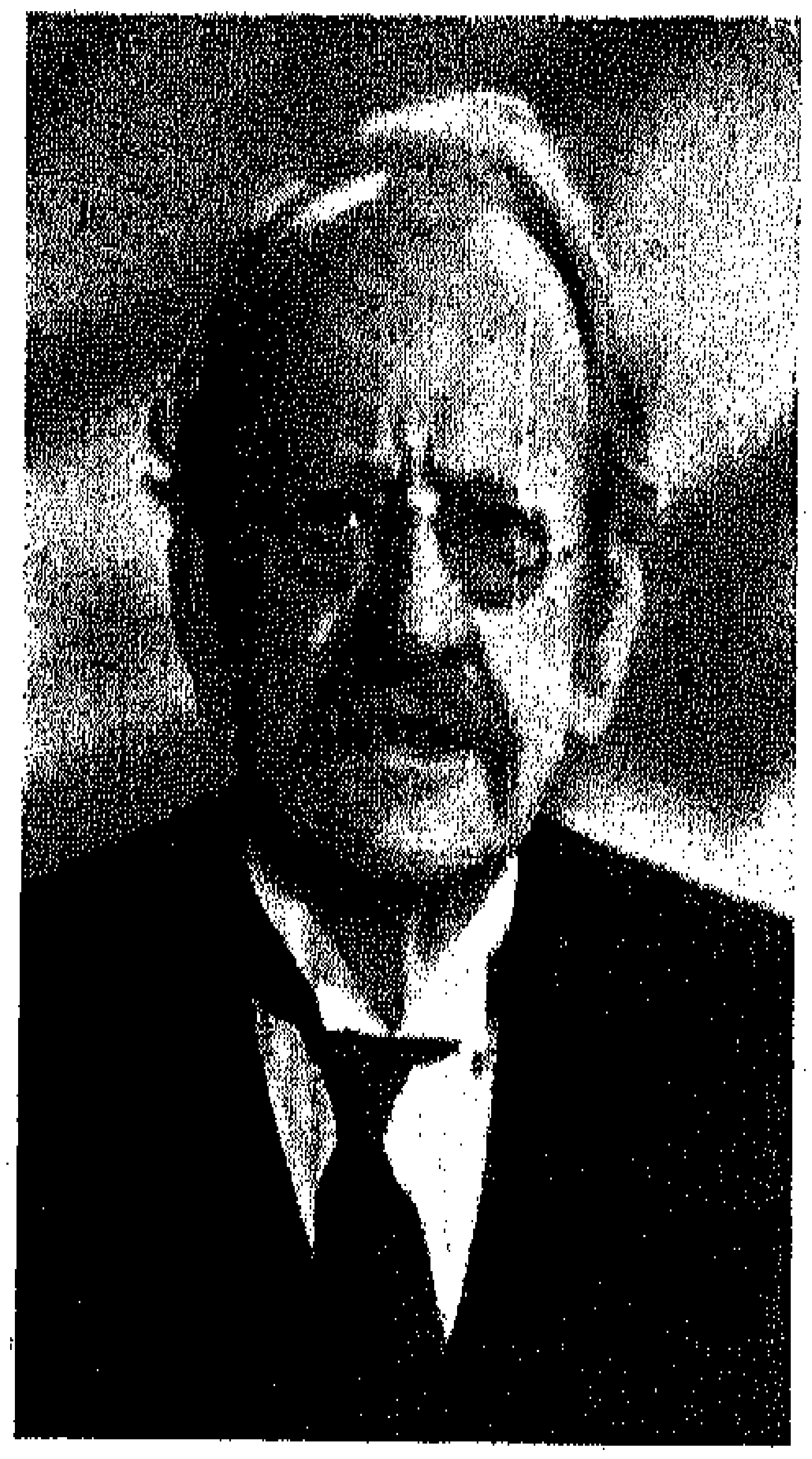


Plate 21: The scale of an atomic-bomb explosion. To give some idea of size, the outlines of some London landmarks have been printed in on the same scale. Their relative position, however, bears no relation to those they actually occupy on the map. (*Copyright in U.S.A. by Julian Mack for the Assn. of Los Alamos Scientists.*)

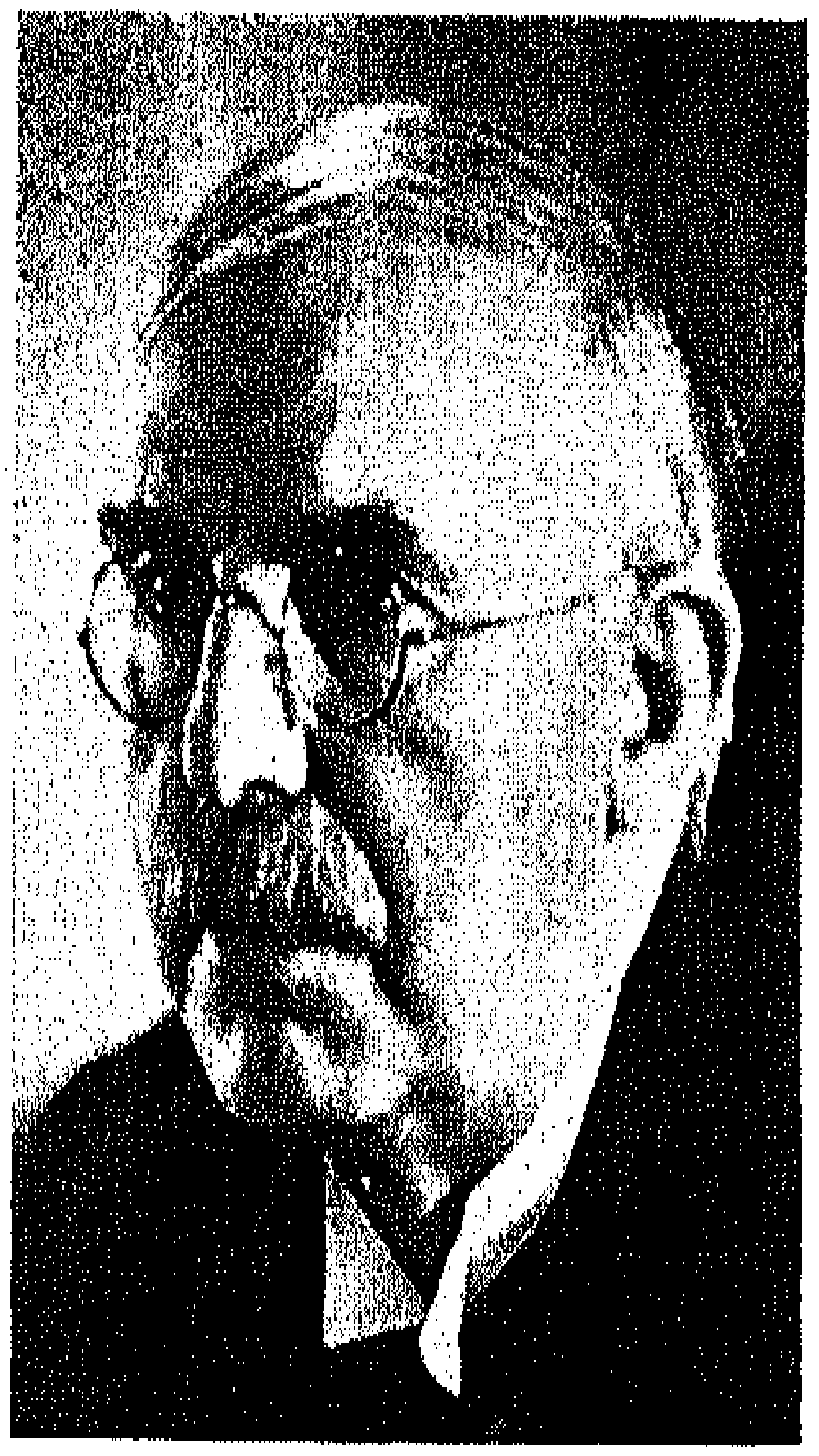
FOUR BRITISH PHYSICISTS

Sir John Cockcroft.
(Fox Photos Ltd.)

Sir James Chadwick.
(Walter Stoneman.)



Sir J. J. Thomson.
(From the G.B. Instructional Film 'Atomic Physics'.)



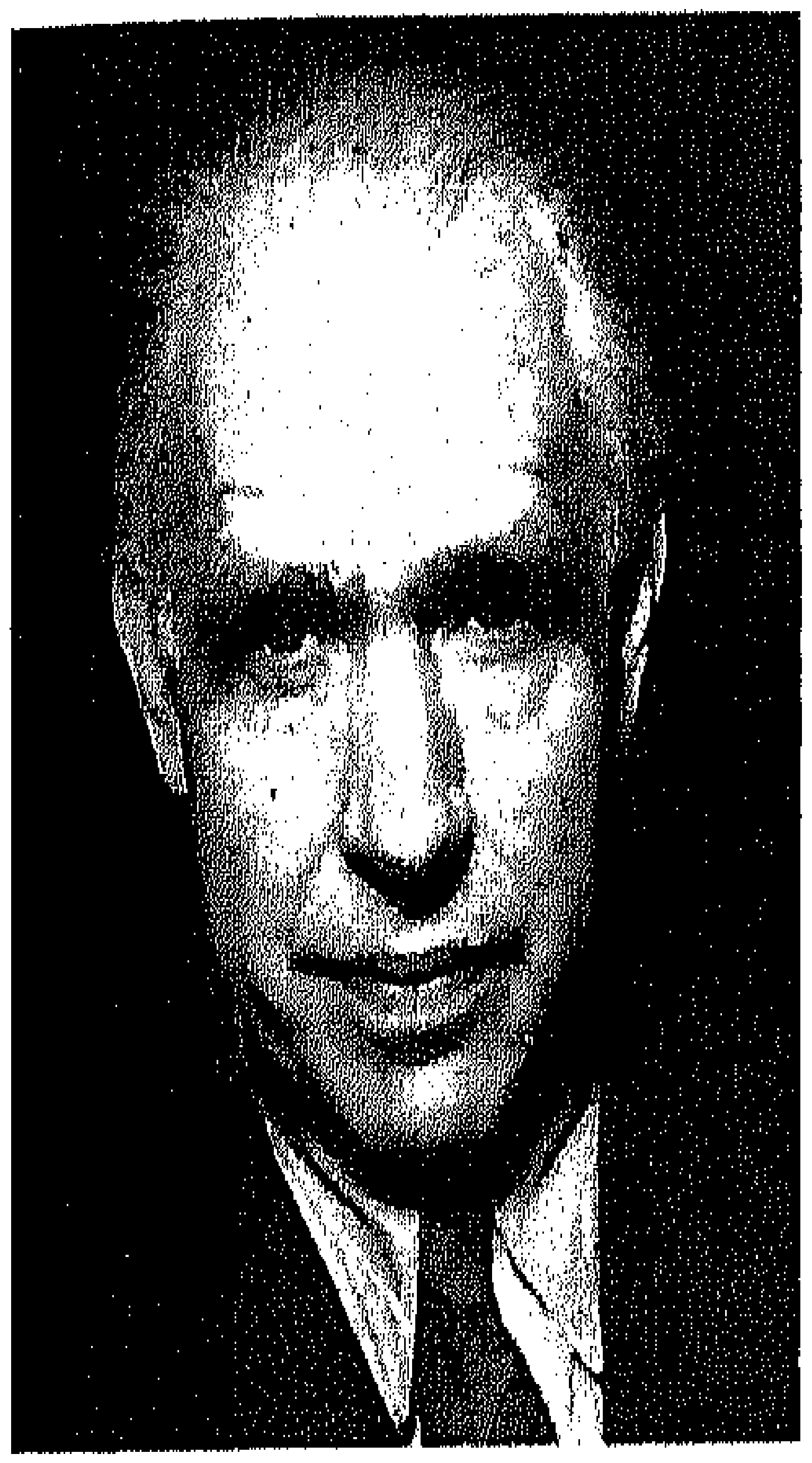
Lord Rutherford.
From the G.B. Instructional Film 'Atomic Physics'.)

PLATE 22

SCIENCE IS INTERNATIONAL

Professor Enrico Fermi
(Italy and U.S.A.).
(Press Association Inc.)

Professor E. O. Lawrence (U.S.A.).
(U.S. Information Service, American Embassy.)



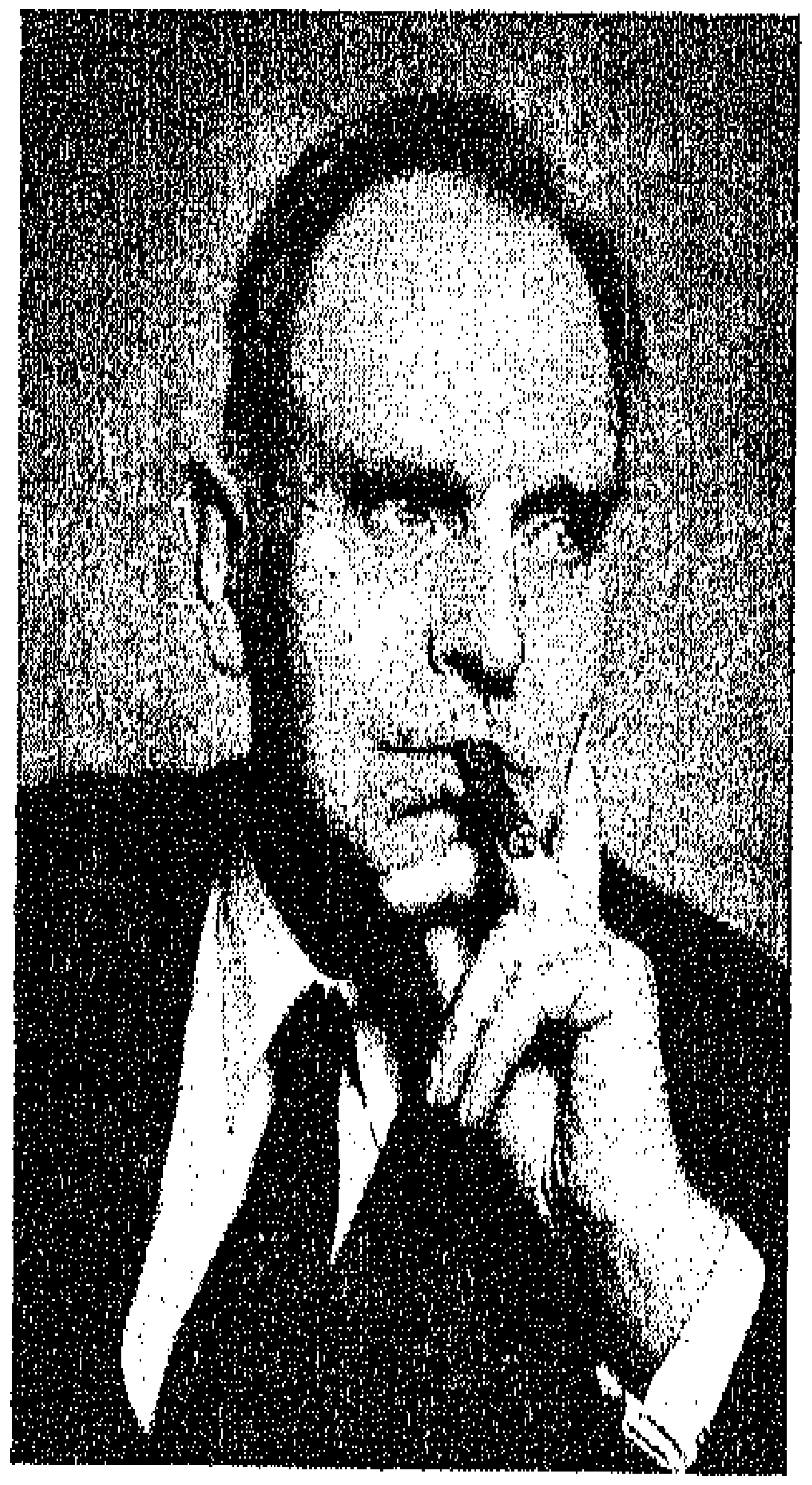
Professor Niels Bohr (Denmark).
(Royal Danish Ministry for Foreign Affairs.)

Professor F. Joliot-Curie (France).
(Planet News Ltd.)

PLATE 23

Dr. J. R. Oppenheimer.
(*International News photo.*)

Professor O. R. Frisch.
(*Lotte Meitner-Graf.*)



Professor Otto Hahn.
(*Lotte Meitner-Graf.*)

Professor Lise Meitner.
(*Lotte Meitner-Graf.*)

PLATE 24

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plant which would use this steam and produce in this way enriched material that would lighten the burden of the electromagnetic plant which was then already in operation.

Lastly, we should here mention another method which was investigated at length, that is the electrolytic method. It is well known that if an electric current is passed through a solution of a salt in water, the electric charge is carried through the solution by the motion of charged atoms or molecules. Just as in the case of a gas, there is some difference in the speed with which the lighter or heavier molecules tend to move, and, in general, the light ones will get slightly ahead of the heavier ones. A nice trick to make this method convenient in practice was suggested independently by several people. It consists in letting the solution pass slowly through the tube in a direction opposite to that of the electric current and arranging the strength of the electric current in such a way that the charged molecules will just stay put. This balance between the backward flow of the solution and the forward flow due to the current will be slightly different for the light and heavy isotopes and in any given part of the tube the light isotope will gradually drift forward and the heavy isotope back. H. London succeeded in measuring the magnitude of this effect and produced a slight separation with it. It turned out, however, that the effect was not favourable enough to compete seriously with other methods of separation.

5. *The Electromagnetic Plant*

All the methods discussed in the three preceding sections are based on principles which allow only a slight enrichment in every stage of the process and which, therefore, have to be applied repeatedly in a large number of stages to obtain nearly pure U 235. We have already seen that, in principle, the mass spectrograph is capable of performing the separation completely in one step, but it always appeared that the translation of this delicate laboratory instrument into in-

Although it would be possible, in principle, to carry out the whole separation in one stage, it turns out that this is not convenient in practice, because the beam carrying the heavy isotope is so much stronger than that carrying the light isotope that very high precision would be needed to get perfect separation in the first step, since one has to avoid any spread on each beam which would mix up even a small fraction of the stronger beam with the weaker one. This would be possible, but it would severely limit the rate at which material could be handled in each unit, and it pays, therefore, to use, instead, a plant that in the first stage will only produce an incomplete separation and to pass the material thus obtained through a second stage, which can now be smaller since it handles a much smaller amount of material, and to complete the separation in the second stage. This second stage is much less of an engineering problem because of its smaller size, but it has to be much more carefully designed. This is because the recovery of material from it must be complete, since the material fed into this stage is very valuable, representing the output of the first expensive plant. The loss of even a small fraction of this material would be serious.

There exist designs for devices working on other principles which are similar to the electromagnetic plant, in that they are capable of producing appreciable separations in a single stage, and which use atomic beams running in conditions of high vacuum so that each atom keeps its own path regardless of the presence of others. The most interesting of these is the 'isotron', which uses a rapidly oscillating electric field which will accelerate and decelerate in rapid succession a beam of charged atoms, when again the light atoms will respond somewhat more quickly to the field than heavy atoms. One can arrange matters in such a way that if a continuous stream of atoms leaves the source they will all meet at a certain point further down the tube because the later arrivals have passed the field at a time when it was accelerating and have been speeded up, whereas the earlier

ones passed at a time when the field tended to decelerate them and have been held back. Because of the different response of the different isotopes the point where the atoms will be accumulated is different for the light and the heavy isotopes, and if arrangements are made to draw off atoms at the right instant from the right point in space, one can arrange to collect preferentially the light ones. This device was developed by R. R. Wilson and probably could also have been turned into a plant of industrial dimensions, but the electro-magnetic plant was more promising and the isotron was abandoned in its favour.

6. *Conclusion*

We have attempted to give a brief sketch of the principles involved in the known methods of isotope separation and of the enormous scale of the operations required for this. All these plants serve the common purpose of producing in a pure or nearly pure form the isotope uranium-235. The next chapter will describe atomic reactors which can be used to produce the element plutonium, which is the other possible atomic fuel. Large-scale plants for both purposes were pushed to completion during the war because it was not known at that time which of the two fuels would be more suitable for making bombs nor how long the actual completion of each plant would take.

In the future, we may hope that the importance of making bombs will gradually be superseded by that of releasing atomic energy for peaceful purposes. In this, the plants are at a disadvantage because the 'piles' described in the next article produce power directly, starting from uranium in its natural form. Nevertheless, for many applications it will be essential to have small and concentrated power units which have to use active material, i.e., pure or nearly pure plutonium, or pure or nearly pure uranium-235. It is too early yet to see through the many factors that govern the economy of these two possibilities, and it is, therefore, not known now whether separation plants will remain a permanent feature of atomic energy projects or whether their function in producing the material used in the first atomic bomb is now a matter of history.

4

Nuclear Reactors

SIR JOHN COCKCROFT, C.B.E., F.R.S.

A VERY great deal has been written on the subject of nuclear power both in the popular press and elsewhere, and much of it is of little value. This has been partly due to the restrictions of security which have resulted from nuclear power being closely linked with nuclear explosions. It has been due also to the many uncertainties which obscure the future and which make predictions depend to some extent on processes analogous to crystal gazing.

This article will be hampered to some extent by both factors, but in each successive year we may hope to be able to speak a little more freely and with more knowledge.

Nuclear power will come from the conversion of heat developed in nuclear reactors to electric power. In the process of fission of uranium, highly energetic fission fragments are produced together with penetrating gamma rays and neutrons having energies of several million electron volts.* The kinetic energy of the fission fragments is of the order of 160 million electron volts, whilst the remaining energy released is of the order of 20 million volts. The kinetic energy of the fission fragments is the important factor in nuclear power.

A nuclear reactor is an assembly of uranium having the property that a nuclear chain reaction can develop. The chain reaction is started by a single neutron producing a

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*An energy of one electron volt is the energy which an electron acquires in dropping through a potential difference of one volt. Neutrons having an energy of a million electron volts are moving with a speed of a little over 10^9 centimetres a second. A symbol such as 10^9 is the scientists' shorthand for a 1 followed by 9 zero.

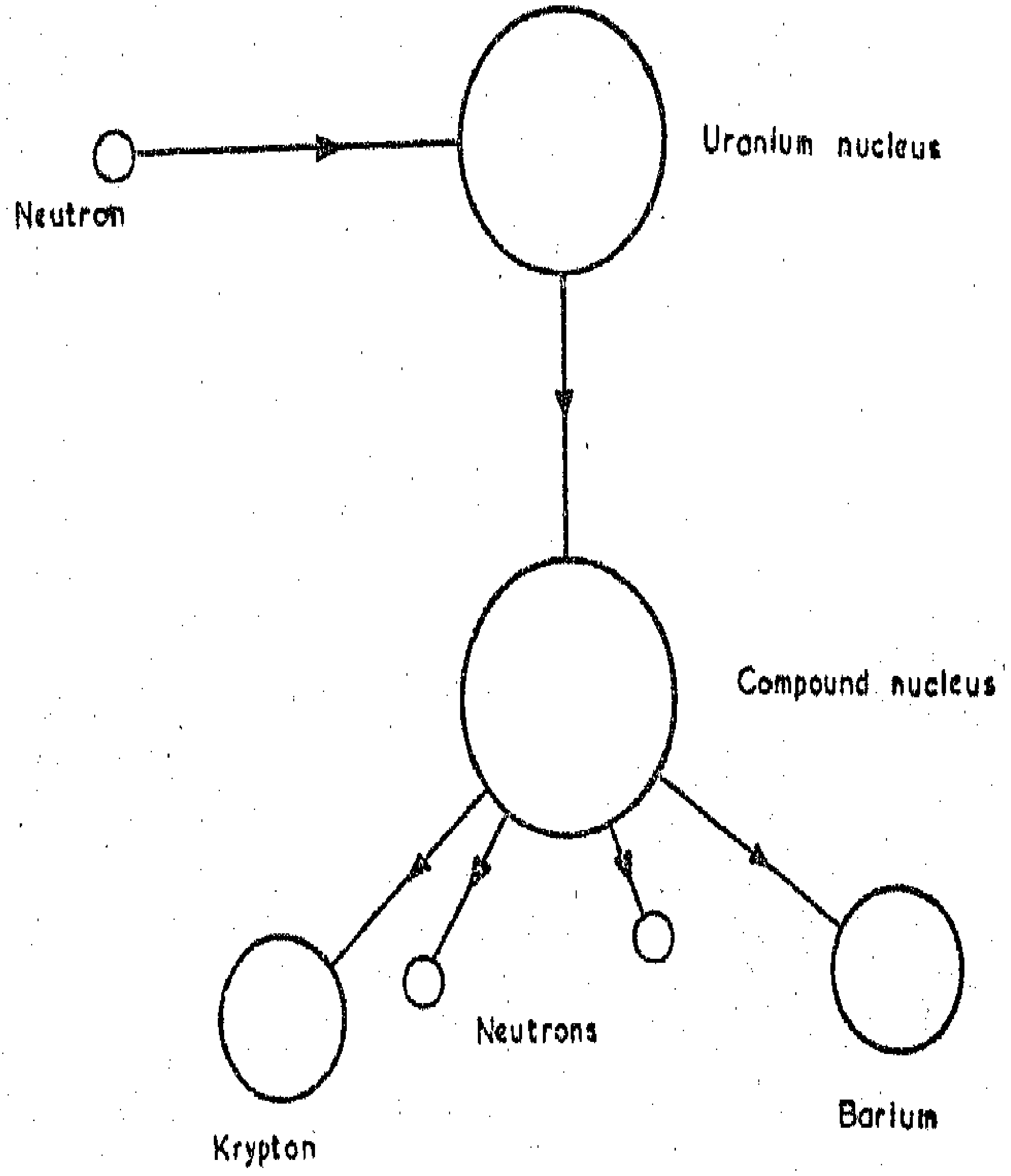


Fig. 2. Fission of uranium.

fission of uranium. In the fission process about two fairly fast neutrons are emitted. The subsequent history of these neutrons decides whether a chain reaction can develop. Neutrons can die in a number of ways. They can be absorbed in most elements with the emission of gamma radiations to signal their death; they can escape from the reactor and be effectively lost or they can survive and produce a further fission. If, in spite of all sources of loss, more than one neutron survives to produce the fission, the chain reaction can develop and the neutron population and number of fissions can increase.

The multiplication factor, K, characterises the relative increase in neutron population in successive generations. K must be equal to or greater than one for a chain reaction to occur. (See Fig. 3, page 73).

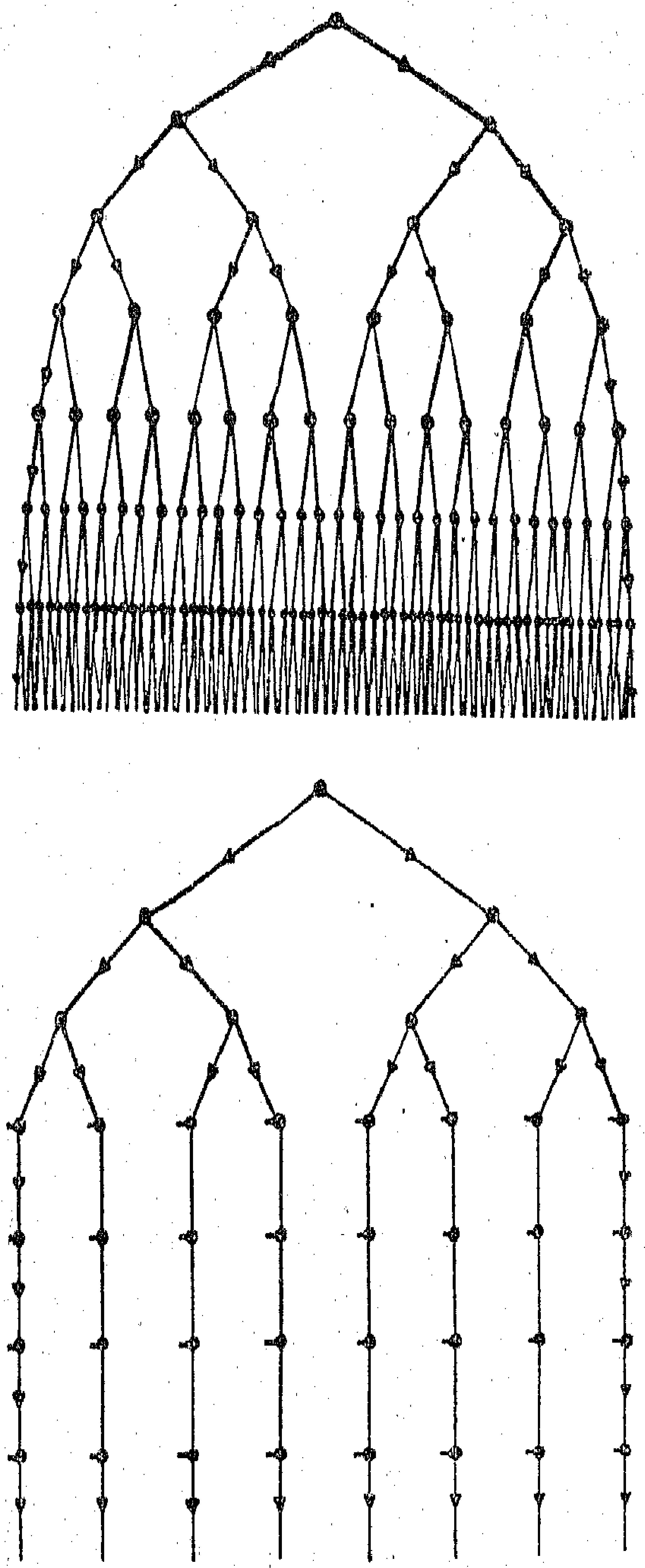


Fig. 3. (Above): *Divergent chain reaction. K greater than* 1.
(Below): *Balanced chain reaction.* $K=1$.

Nuclear reactors fall into three broad types. The first type is known as the fast reactor, because the neutrons produce further fissions whilst they are still moving with high speeds.

Fig. 4 shows diagrammatically how the fission of uranium-235 depends on neutron energy. The fission probability (*vertical* in diagram) is fairly constant as the neutron energy falls from its initial energy of about one million volts and then starts to rise quite a lot. In the case of U 238, however, the fission probability falls to zero at energies of about a million volts. Now since neutrons lose energy fairly quickly in collisions and since also U 238 may absorb neutrons without producing fission, it turns out that a fast chain reaction cannot develop in a mass of uranium metal which has the normal proportion of one part of U 235 and 140 parts of U 238. If, on the other hand, we remove, with great expense and effort, the greater part of the U 238, the chain reaction can develop if we have a sufficiently large mass of the U 235. As we put more and more of the U 235 together, the proportion of neutrons escaping from the reactor becomes smaller and K increases towards unity.

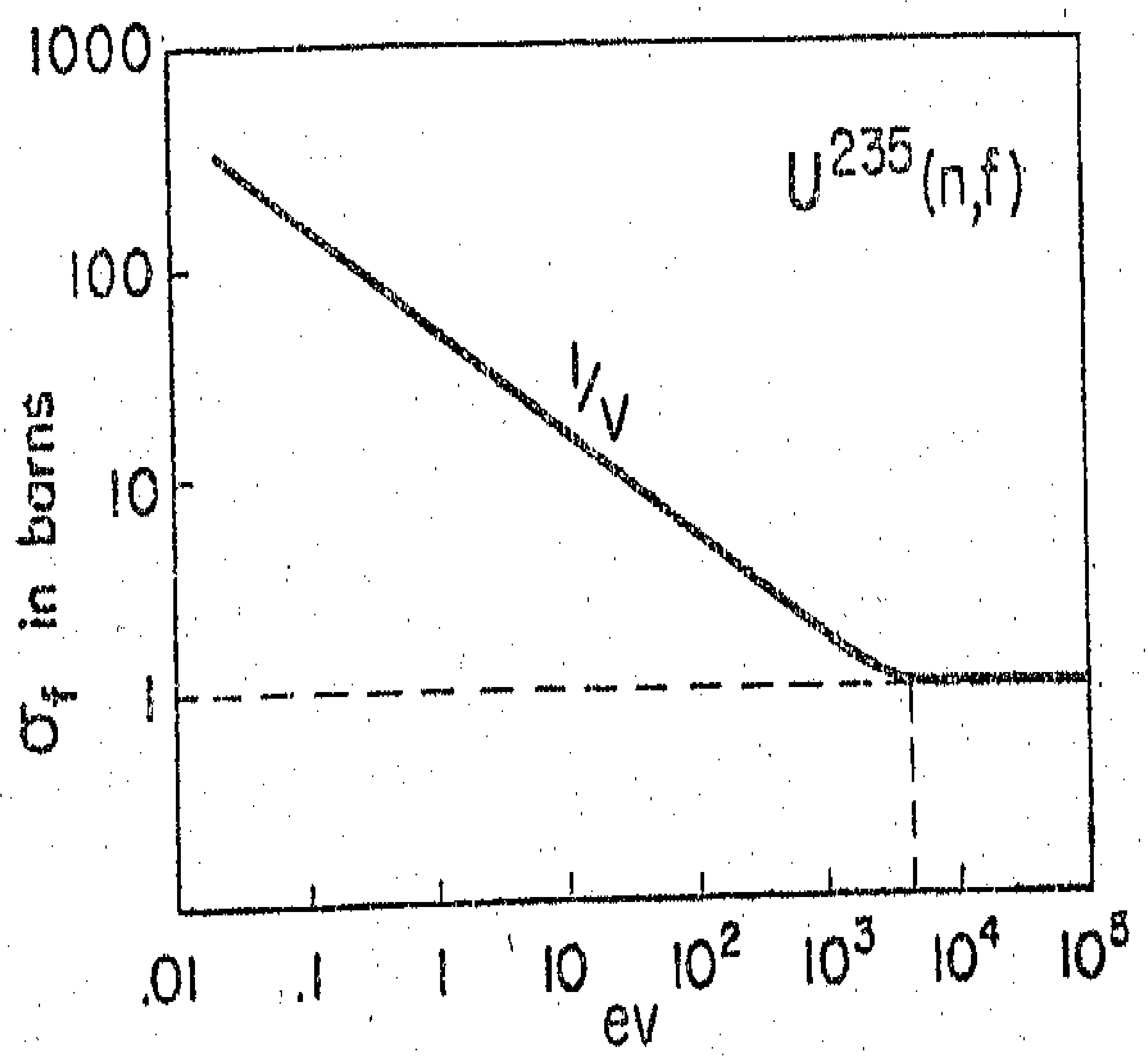


Fig. 4. Probability of fission of U 235 *nucleus by neutrons of varying energy,* ev. (*From 'The Science and Engineering of Nuclear Power', ed. Clark Goodman, by courtesy of the publishers, Addison Wesley Press Inc., Cambridge, Mass.*)

When K is just less than unity, one neutron will produce

$$1+K+K^2+K^3+\ldots=\frac{1}{1-K} \text{ neutrons.}$$

Some neutrons are always available either from cosmic rays or from the small rate of spontaneous fission of uranium. We shall therefore find a rapid increase in the number of neutrons as we approach the critical point when $K=1$. Up to this point, however, the number of neutrons is on the average constant in time. There will be fluctuations but no build-up. When, however, we add a little more uranium to the critical quantity, K becomes greater than unity, and the number of neutrons and fissions will begin to grow exponentially with time, and we might expect them to follow the relation

$$N=N_0e^{(K-1)t/\tau}$$

where τ is the lifetime of one generation of neutrons and is of the order of 10^{-8} seconds. If then K were to exceed unity by a tenth of 1 per cent the time constant of the reaction would be 10^{-5} seconds, so that the system would be somewhat difficult to control.

We are, however, saved from this difficulty by the fact that a small proportion, about 1 per cent, of the neutrons resulting from fission appear late – they may be delayed by up to a minute. This is because some of the fission fragments are radioactive and evaporate neutrons after times of this order. If then our excess K is less than 1 per cent, we have to wait for several seconds for an effective population increase to occur. This allows the system to be controlled.

Fast reactors require considerable quantities of scarce fissile material such as U 235. For this reason they have so far been built only in the United States. They are interesting because of their potentialities as breeders of fissile material. I will say more about breeding later. Few details of their practical construction have been released. Essentially, however, they consist of fissile material, U235, in the form of metal through which flows a gaseous or liquid metal coolant, circulating in a closed system.

The more usual type of nuclear reactor is the slow neutron reactor. This reactor makes use of the fact shown in Fig. 4 that as neutrons are slowed down, the probability of their producing fissions in U235 increases. It is possible, therefore, for a chain reaction to develop in a mass of natural uranium if it is embedded in a medium which has the property of slowing down neutrons without swallowing them up. Such a medium is known as a moderator. To be an effective slower down, the moderator must be composed of light atoms which do not capture neutrons. The only possible moderators turn out to be carbon, beryllium or heavy water. Ordinary water captures too many neutrons to allow K to reach unity even for a very large system.

Beryllium is rather scarce in nature and is certainly very expensive, and is somewhat toxic, and so only two types of slow reactor have been built, the graphite reactor and the heavy water reactor.

The general considerations about the multiplication constant of the fast reactor apply equally to the slow reactor. The lifetime of a neutron generation is now about a millisecond owing to the time taken to slow down, a hundred thousand times longer than for the fast reaction, but the time constant would be still too short for comfort were it not that delayed neutrons again make control possible.

The critical size of a slow reactor depends on the multiplication factor and on the distance, M, a neutron travels between birth and death, the linear dimensions being given by

$$a \approx \frac{M}{\sqrt{K-1}}$$

Here K is the multiplication factor for an infinite system. For a graphite system K cannot exceed 1.07 and for a heavy water system cannot exceed 1.15. Heavy water reactors can

therefore be smaller than graphite reactors, which require several hundred tons of graphite and tens of tons of uranium metal.

If structural materials which absorb neutrons are used in the reactor this will reduce K below the ideal figure of 1.07 and the size of the reactor grows accordingly. Power-producing reactors must use some metals in their coolant circuit, but the amount of this metal must be strictly limited, and the engineer must choose lightly absorbing metals such as aluminium or magnesium for use in his coolant circuits.

Loss of neutrons from the reactor is reduced and K thereby increased by surrounding the reacting core by a reflector of graphite which reflects back a high proportion of the escaping neutrons into the core.

Plate 7 shows the first pile built at Harwell, known locally as the 'Gleep' – Graphite Low Energy Experimental Pile. It contains a minimum of metal in its reacting core; it has

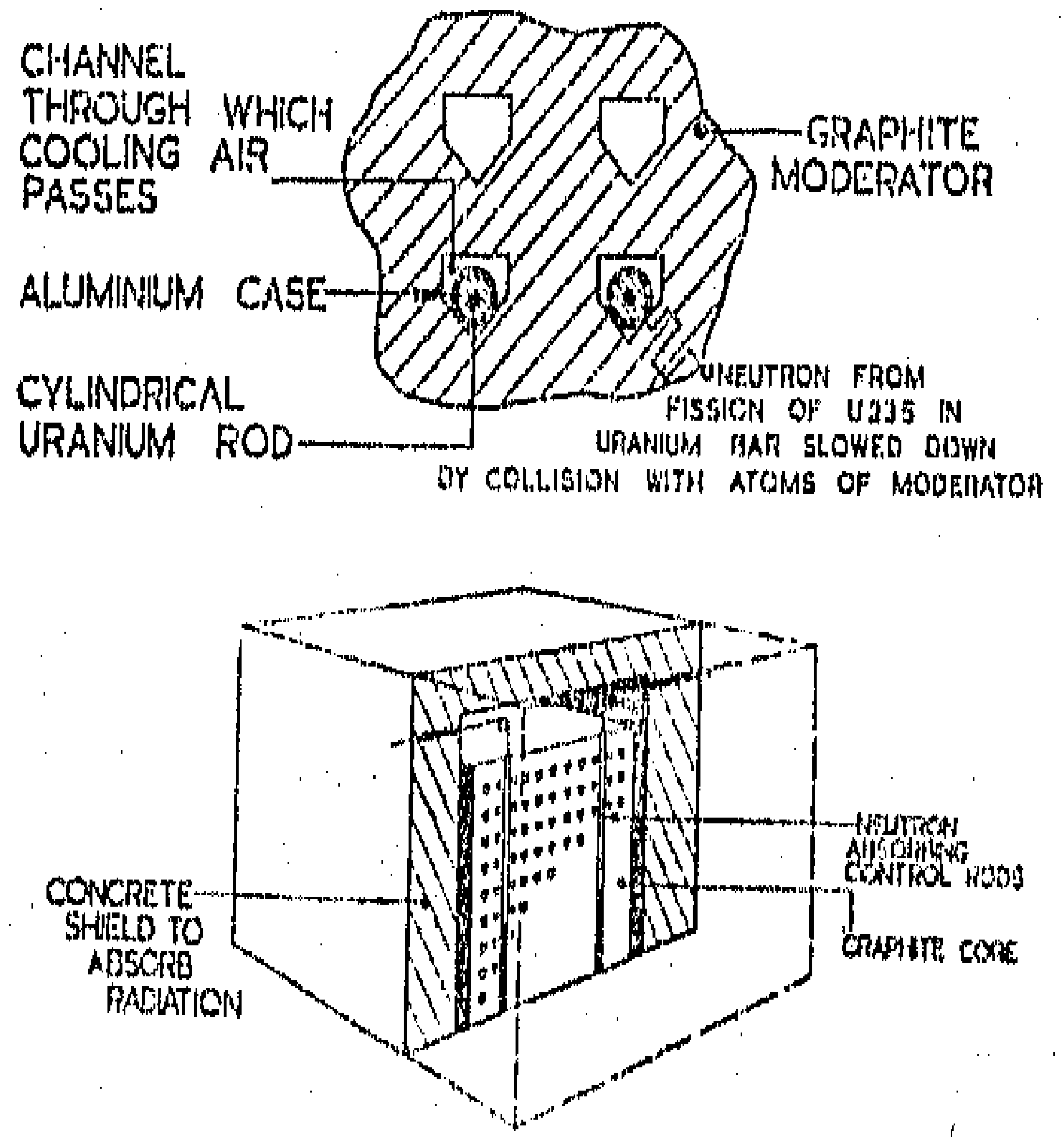
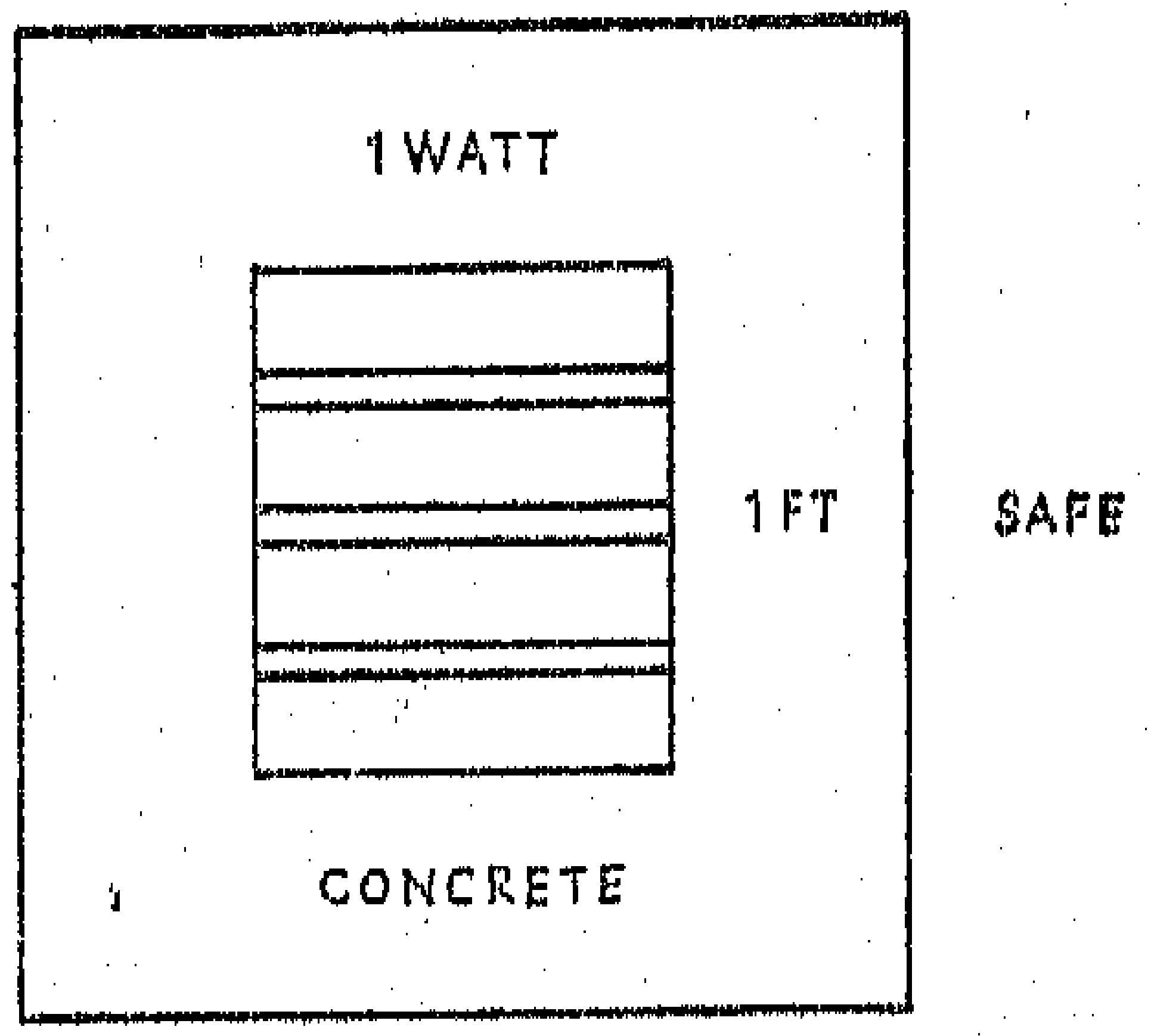

CHANNEL THROUGH WHICH COOLING AIR PASSES
GRAPHITE MODERATOR
ALUMINIUM CASE
CYLINDRICAL URANIUM ROD
NEUTRON FROM FISSION OF U235 IN URANIUM BAR SLOWED DOWN BY COLLISION WITH ATOMS OF MODERATOR
NEUTRON ABSORBING CONTROL RODS
CONCRETE SHIELD TO ABSORB RADIATION
GRAPHITE CORE

Fig. 5. Section through pile, in detail above, a scheme of the whole below. (Copyright.)

practically no cooling; it is surrounded by a concrete shield to reduce the intensity of radiations reaching the exterior. Fig. 5 illustrates the construction.

As the nuclear reaction proceeds, heat is developed in the uranium metal rods owing to the fast-moving fission fragments dissipating their kinetic energy there. In each fission process high-energy gamma rays are emitted and in addition the fission fragments – the pieces into which the uranium is split – are radioactive and emit electrons and gamma rays. The amount of radioactivity developed is proportional to the heat developed, and a rough calculation shows that a pile developing the heat equivalent of one watt will emit radiations roughly equivalent to those emitted by a gram of radium. Now a gram of radium must be shielded by about one foot of concrete to make it safe to sit on. Each additional foot of concrete will reduce the radiation intensity by a factor of about 10, so that for each increase of power by a factor of 10 we require one more foot of concrete in the shield. A pile such as the Gleep operating at 100 kW requires therefore about six feet of concrete in its shield.



I WATT POWER LEVEL REQUIRES I FOOT CONCRETE
10^6 WATT POWER LEVEL REQUIRES 7 FEET CONCRETE

Fig. 6. Pile shielding.

The control of a pile is effected by winding in or out neutron-absorbing control rods which decrease or increase K. The control rods contain a metal such as cadmium or boron which has a high absorption for neutrons. To increase the power we wind out the control rods and give the

pile some excess K. We then find that the power increases as

$$W = W_0 e^{10^5(K-1)t/2.5}$$

where t is measured in hours. An excess K of one part in 10^5 will lead to a pile period of 2.5 hours. We usually wind out the control rods to give the pile a period of a minute or so and bring up the power to the desired level. The control rods are then wound in again till K=1 and the power then levels off. Plate 8 shows the control room of the Gleep.

The Gleep has quite specific duties in our Atomic Energy programme. It is required particularly for measuring the neutron-absorption properties of elements which are important in the work. It is able to do this because of the great sensitivity of pile power to excess of K. If, for example, we insert into the pile as little as one milligram of boron we can detect the decrease of pile power it will produce. We therefore insert and withdraw a specimen into the pile cyclically and measure the modulation of pile power. Fig. 7 shows a typical record.

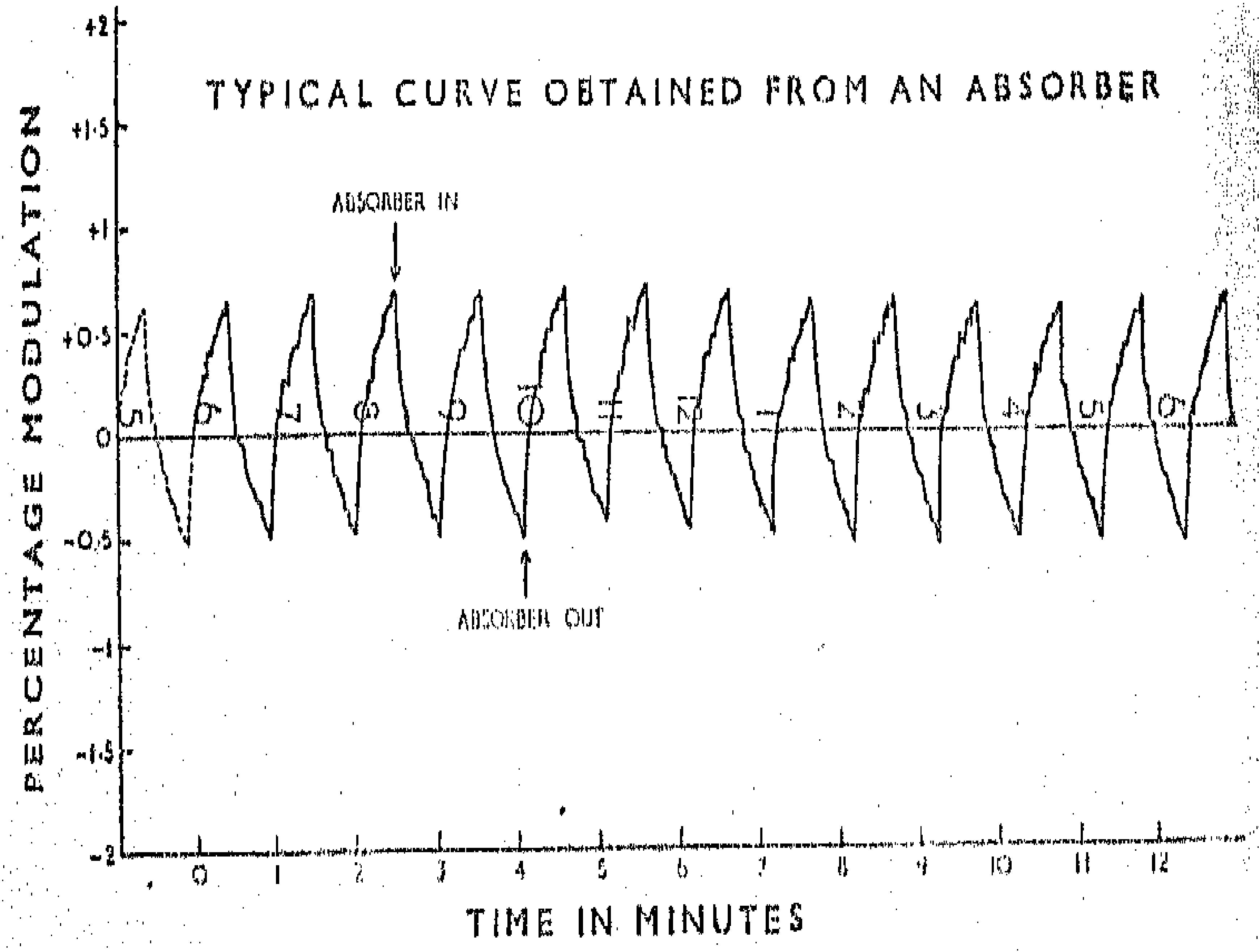


Fig. 7. Pile power modulated by cyclical insertion and withdrawal of neutron-absorbing material. (*Copyright.*)

Table I shows typical neutron-absorption properties of the elements.

ABSORPTION COEFFICIENTS OF THERMAL NEUTRONS

	Element	σ (x 10^{-24}) sq. cm.
LOW	D	.0006
	Be	.0085
	C	.0048
MEDIUM	Mg	.06
	Al	.24
	Pb	.17
	Fe	2.5
HIGH	B	700
	Cd	2500
	Au	95
	Li	65
	Ag	57
	He^3	3500

Table 1. *Absorption coefficients of Thermal Neutrons.*

The second pile built at Harwell, the B.E.P.O., was designed to develop a heat equivalent of 6000 kilowatts and a corresponding higher intensity of radiation. We had therefore to remove this substantial heat by intensive air cooling. Plate 2 shows the exterior of the pile building with the high stack through which the cooling air is exhausted. One of the principal functions of this pile is to test the effect of the intense pile radiations on the properties of materials. The very energetic neutrons inside a pile bombard the atoms of solids and displace atoms from their normal position in the crystal lattice. As a result of this bombardment, physical properties, the elastic properties, the thermal and electrical conductivity, the mechanical strength, all change. As an example of these changes, Fig. 8 shows the effect of pile radiations on a rectifying crystal such as germanium.

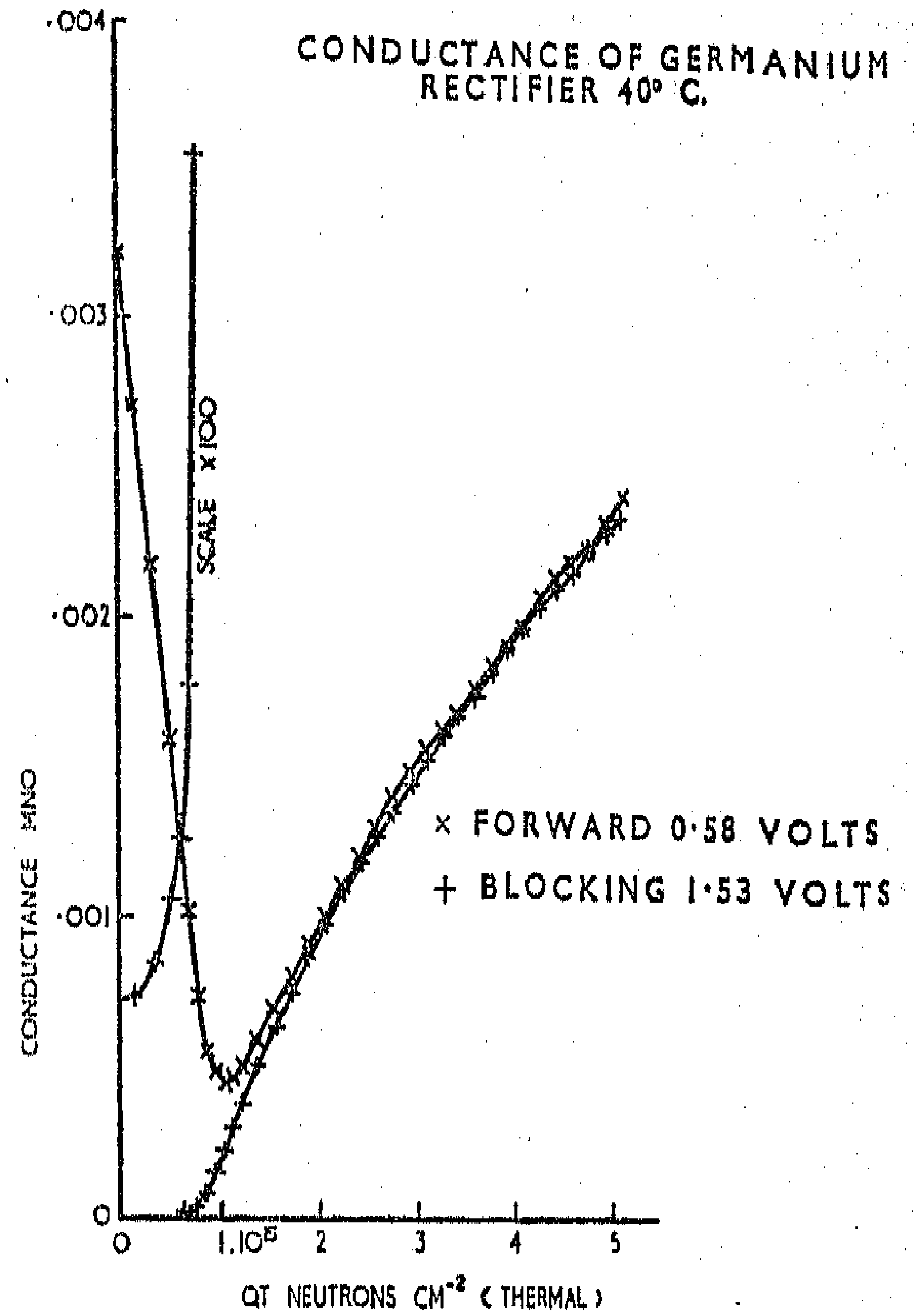


Fig. 8. *Conductance of Germanium Rectifier under fast neutron bombardment.* (*Copyright.*)

The upper curve shows the variation of the electrical conductivity of germanium in the conducting direction. As the germanium is bombarded, this conductivity falls, reaches a minimum and then rises again. The lower curve shows the conductivity in the reverse, blocking, direction. It starts at such a low value that the early part of the curve has to be drawn on 100 times the scale. This blocking conductivity *rises* under bombardment until after an irradiation of one day it equals the conductivity in the other direction. The rectification properties of the germanium have therefore been destroyed. This is due to atoms being knocked out of the lattice into interlattice positions where they act as centres sucking up the conduction electrons of the rectifier. The amount of the change increases with the intensity of the fast neutron bombardment – the higher the specific power level the more important do these changes become. Since power-producing reactors will operate at very high specific powers it is essential to the designer to know what is going to happen to his materials. Reactors such as the B.E.P.O. are therefore also essential in an atomic energy programme.

In addition to this purely technological interest of medium power reactors they have important applications to nuclear physics and to the physics of solid structure. This is because we can obtain from the reactor intense beams of fast or slow neutrons. Now neutrons having speeds of the order of 10^5 cms a second are associated with a De Broglie wave length of the order of one angstrom – a wave length of the order of X-ray wavelengths.

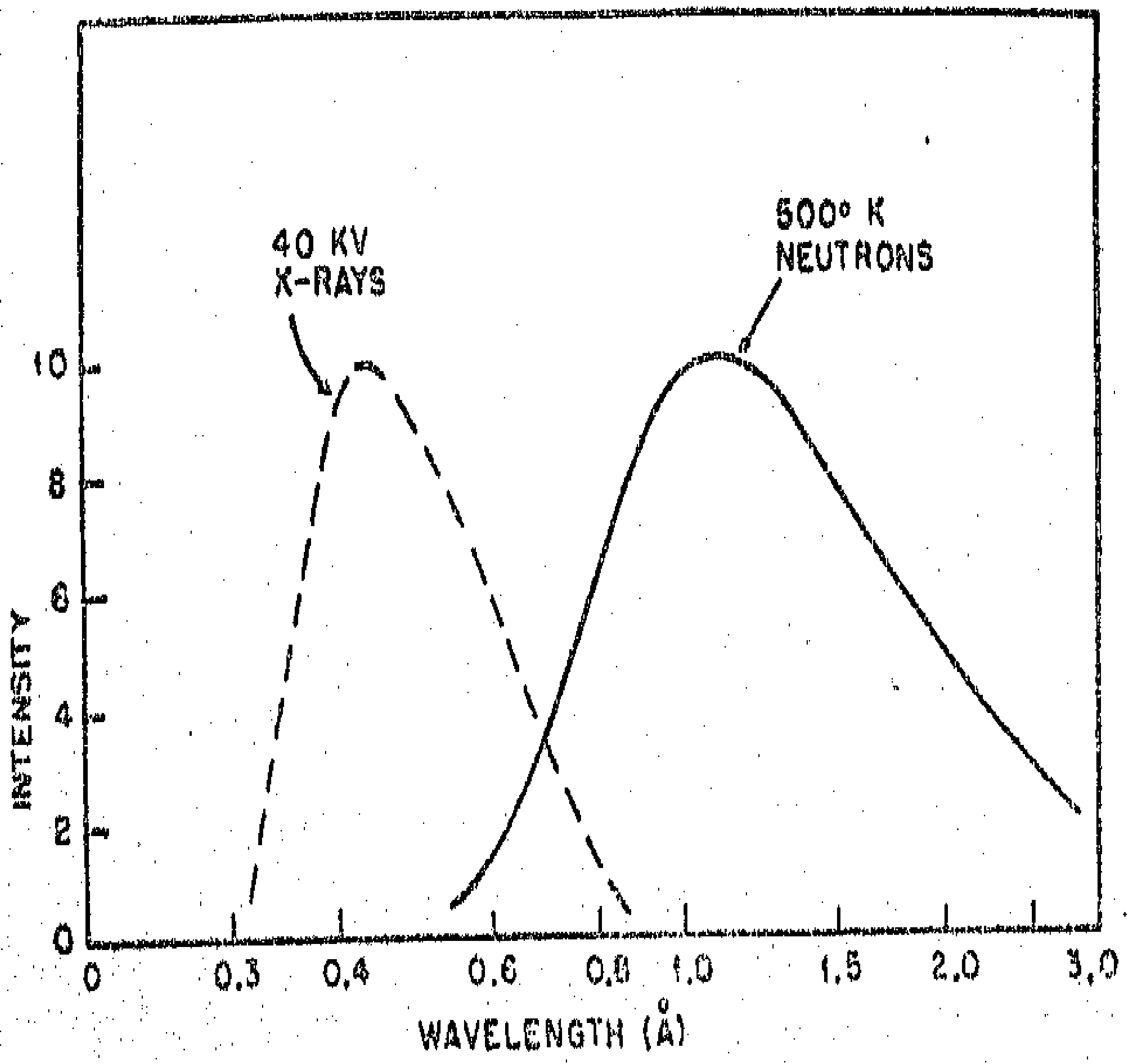


Fig. 9. Distribution of intensity in typical X-ray and neutron spectra (U.S. M.D.D.C. report).

We can therefore use neutrons, like X-rays, to determine the position of atoms in a crystal. Fig. 10 shows the arrangement used to take Laue type diffraction pictures. A beam of collimated slow neutrons is brought through the pile shield and allowed to fall on a crystal. The diffracted beam strikes an indium foil and makes it radioactive. Behind this is placed a photographic plate so that spots appear at the position of the diffracted beams.

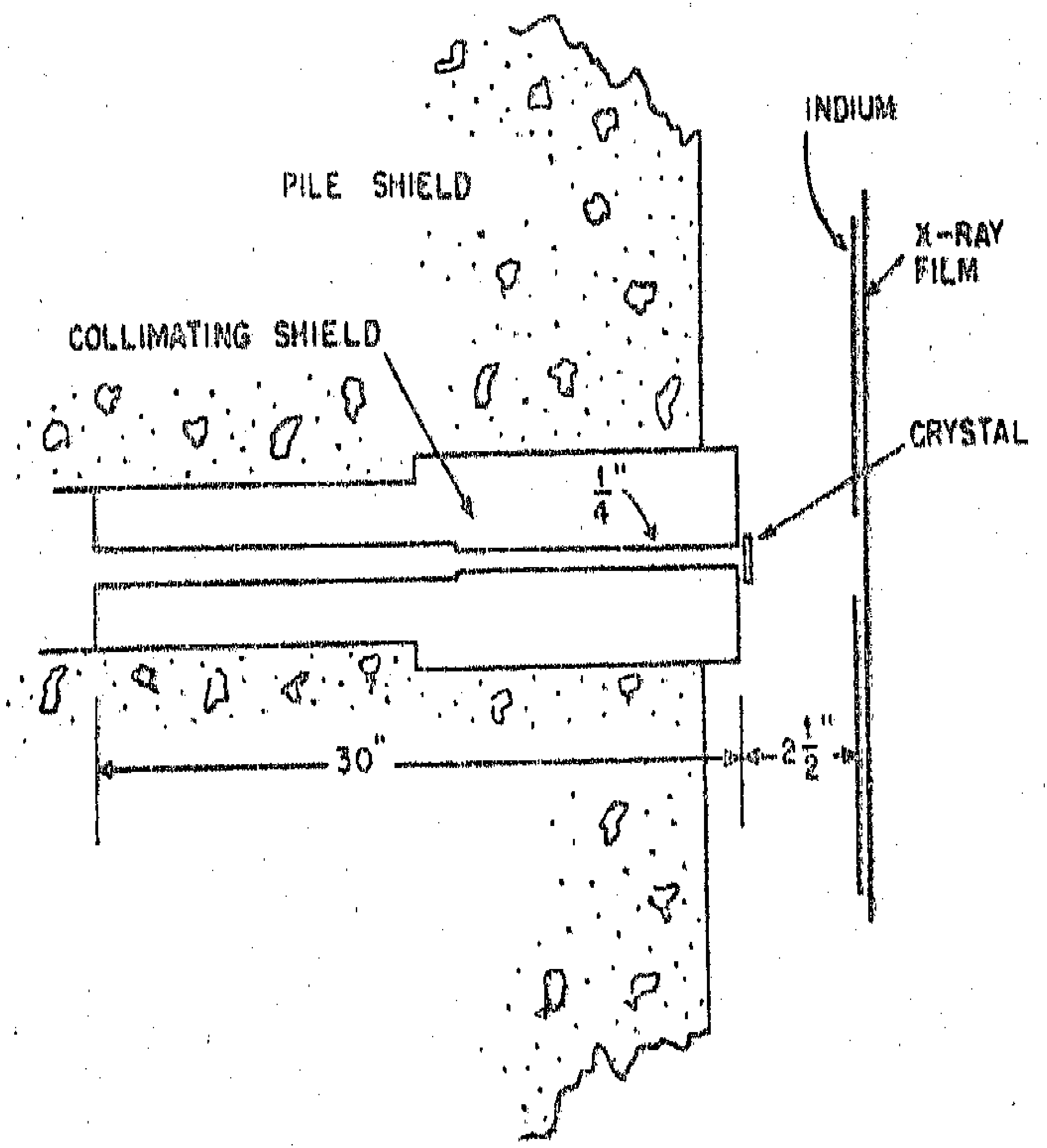


Fig. 10. Schematic diagram of neutron diffraction camera for taking Laue photographs (U.S. M.D.D.C. report).

The next two figures, 11 and 12, show the diffraction pattern for a NaCl and a LiAF crystal. These crystals both have face-centred cubic lattices.

The neutrons can also be used in the Debye-Scherrer method of powder photography. A monochromatic beam of neutrons is selected by Bragg reflection from the face of a crystal (Fig. 13).

The beam is passed through a powder spectrometer and the reflected peaks observed.

Fig. 14 shows the patterns obtained by X-rays and neutrons for copper powder. It will be seen that the resolution obtained by neutrons is less than with X-rays. The X-ray intensities decrease with higher angles owing to interference effects from different parts of the electronic structure, whereas there is no such effect for neutrons. Fig. 15 shows the results obtained for MnO. Here there is a great difference in

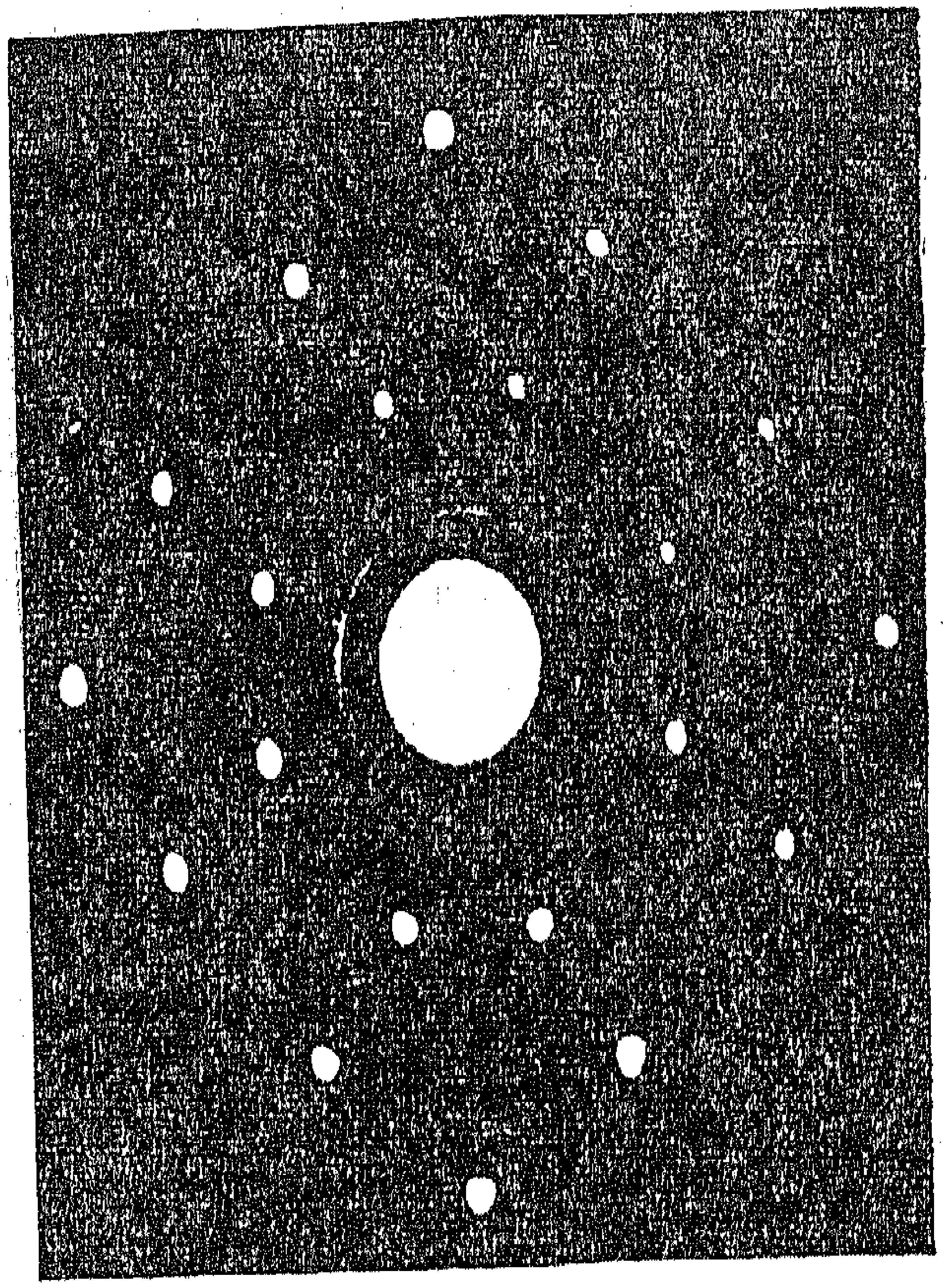


Fig. 11. Laue pattern for NaCl. X-ray film by itself is quite insensitive to neutrons so that it is necessary to place some activating substance next to the film to produce darkening at the Laue spot positions. A sheet of indium has been used for this purpose and the beta particles given off upon neutron capture in indium mark the film at positions where a neutron beam has been diffracted (U.S. M.D.D.C. report).

the pattern of the peaks owing to the fact that the nuclei of Mn and O scatter in opposite phase – about four kinds of nuclei scatter in negative phase. Neutron spectroscopy will be important because it enables the position of light atoms in crystals to be determined in cases where X-rays fail to determine their position.

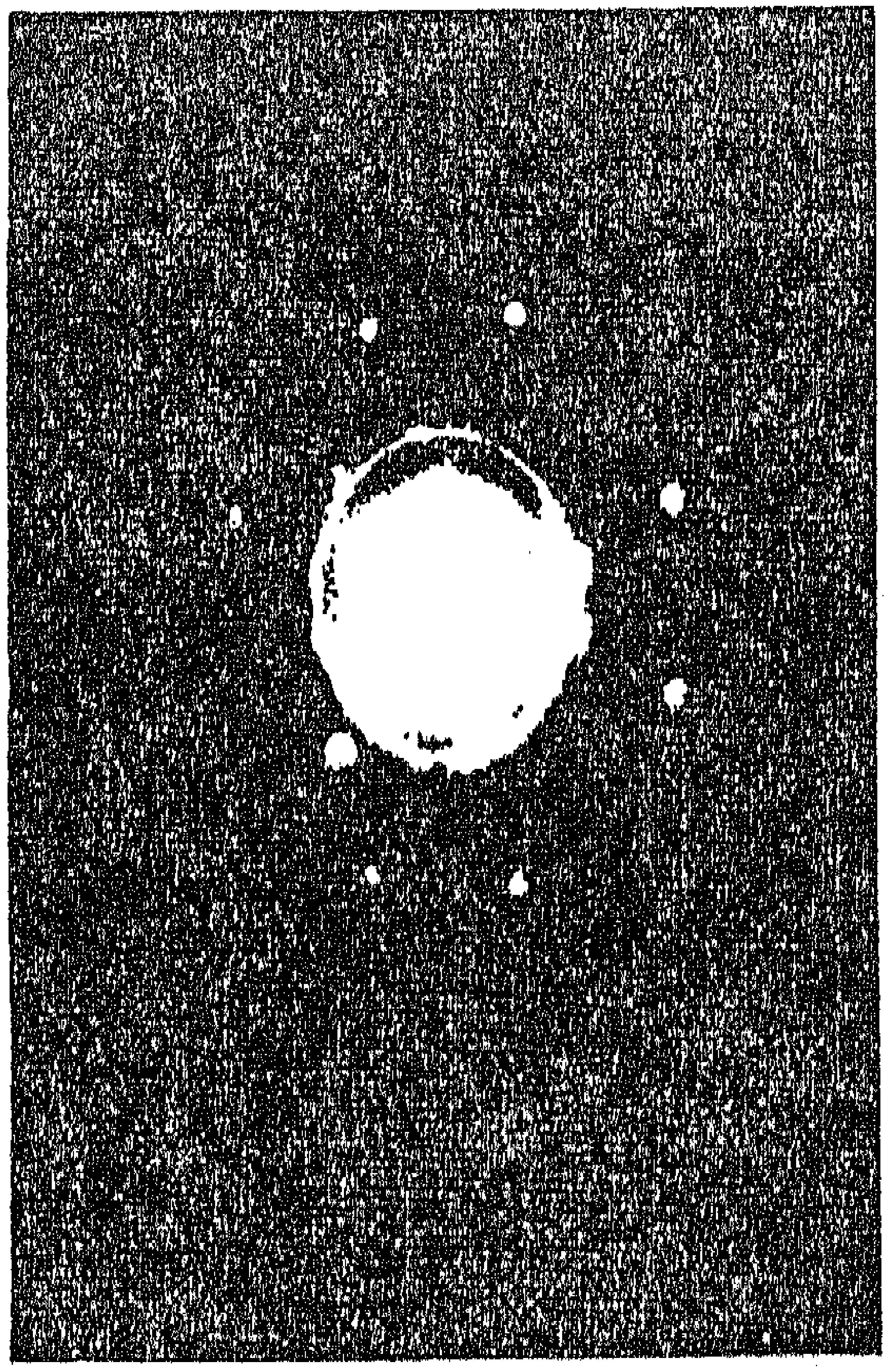


Fig. 12. Laue pattern for LiF (U.S. M.D.D.C. report).

Future reactor development is likely to split into two lines. We shall be interested in building research reactors to give neutron fluxes one or two orders of magnitude higher than existing reactors. Such reactors are required both as research tools and for the testing of materials to be used in future pile technology. In order to obtain higher neutron fluxes we must increase the specific power of the reactor – that is, the power per unit mass of fissile material, since this is a measure of the rate of fission. At the same time we do not wish to be embarrassed by having to dissipate large quantities of heat – for this costs money; we therefore require to keep the total volume of fissile material as small as possible. But the critical size of the reactor depends on $\frac{M}{\sqrt{K-1}}$, so we must increase K. The only way we can do this is by increasing the proportion of U235 above the natural proportion of 1/140. We are driven then to build 'enriched reactors' – reactors in which the proportion of U 235 is increased several fold above the normal. If we go to the limit and use pure U 235 the total mass of fissile material required is only a few hundred grams, and we can make a reactor by dissolving this in a few litres of water. Such a reactor, known as the 'water boiler', was built at Los Alamos. In spite of its apparent simplicity, such a reactor has objectionable qualities if it is used to develop any appreciable amount of heat, owing to the large amount of short-lived radioactive fission products which are given off.

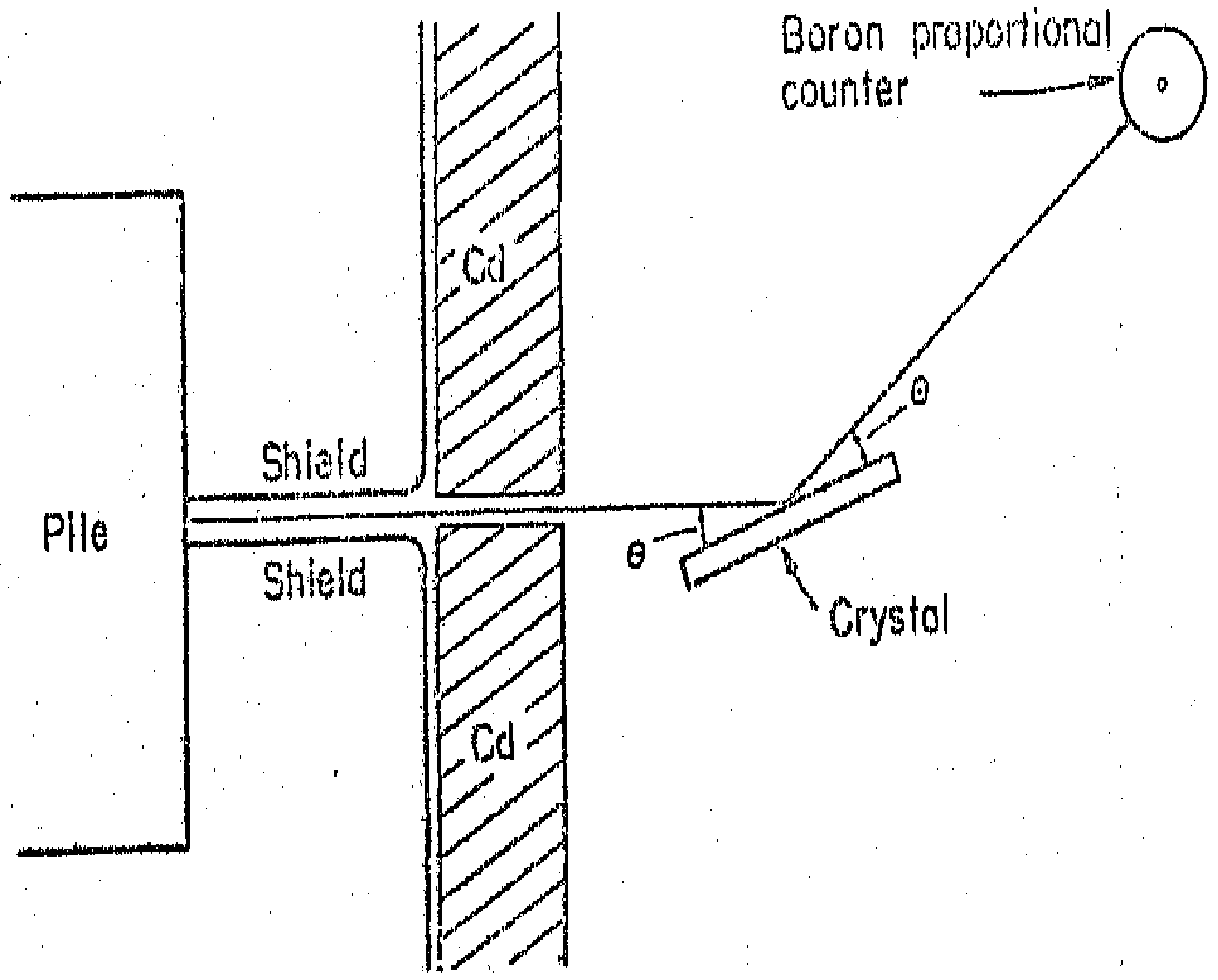


Fig. 13. (*From 'The Science and Engineering of Nuclear Power; ed. Clark Goodman, by courtesy of the publishers, Addison Wesley Press Inc., Cambridge, Mass, U.S.A.*)

The other branch of reactor development is towards obtaining useful and economical power.

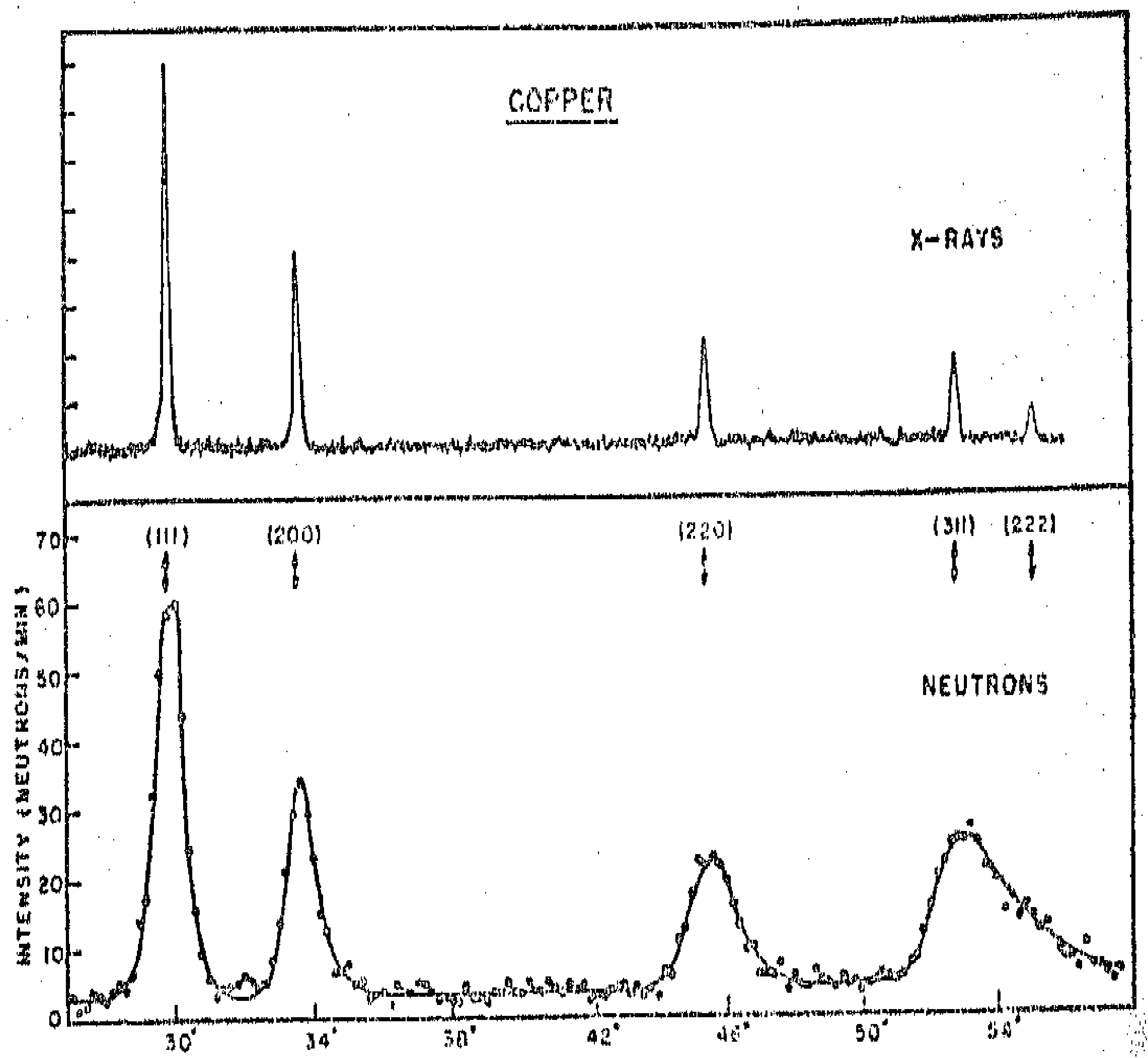


Fig. 14. *X-ray and neutron powder diffraction patterns taken with copper powder. The lower resolution obtainable with neutron sources at present available is to be noted. Also of interest is the form factor decrease of X-ray intensity at the higher angles. The integrated intensities of the* (311) *and* (111) *neutron peaks are about equal, whereas with X-rays they are as* 1 : 3. (*By courtesy of the American Association for the Advancement of Science, from an article by C. G. Shull and E. O. Wollan, 'Science', July* 23, 1948.)

The first line of attack is to look critically at natural uranium reactors. It is fairly obvious that these reactors can be built to develop quite adequate amounts of heat to provide for a fair-sized power station. An important question is whether the heat can be developed at a high enough temperature to make good thermodynamic efficiencies possible. Here we come up at once against the question of permissible reactor materials and the amount of excess K available to us. We do in fact find ourselves severely limited in the number of neutrons we can spare for absorption in the coolant tubes which the engineer must have. Furthermore, we are up against the somewhat capricious behaviour of nature in allocating the neutron-absorbing properties of the elements. The common materials of construction such as steel and nickel have too high an absorption for neutrons, and we are driven back on to metals such as aluminium, magnesium, beryllium, which have objectionable properties such as low melting points or scarcity. This therefore limits our temperature, though it will still permit reasonable efficiencies. Such reactors might circulate a gas through a waste heat boiler and generate steam to drive a turbine (Fig. 16).

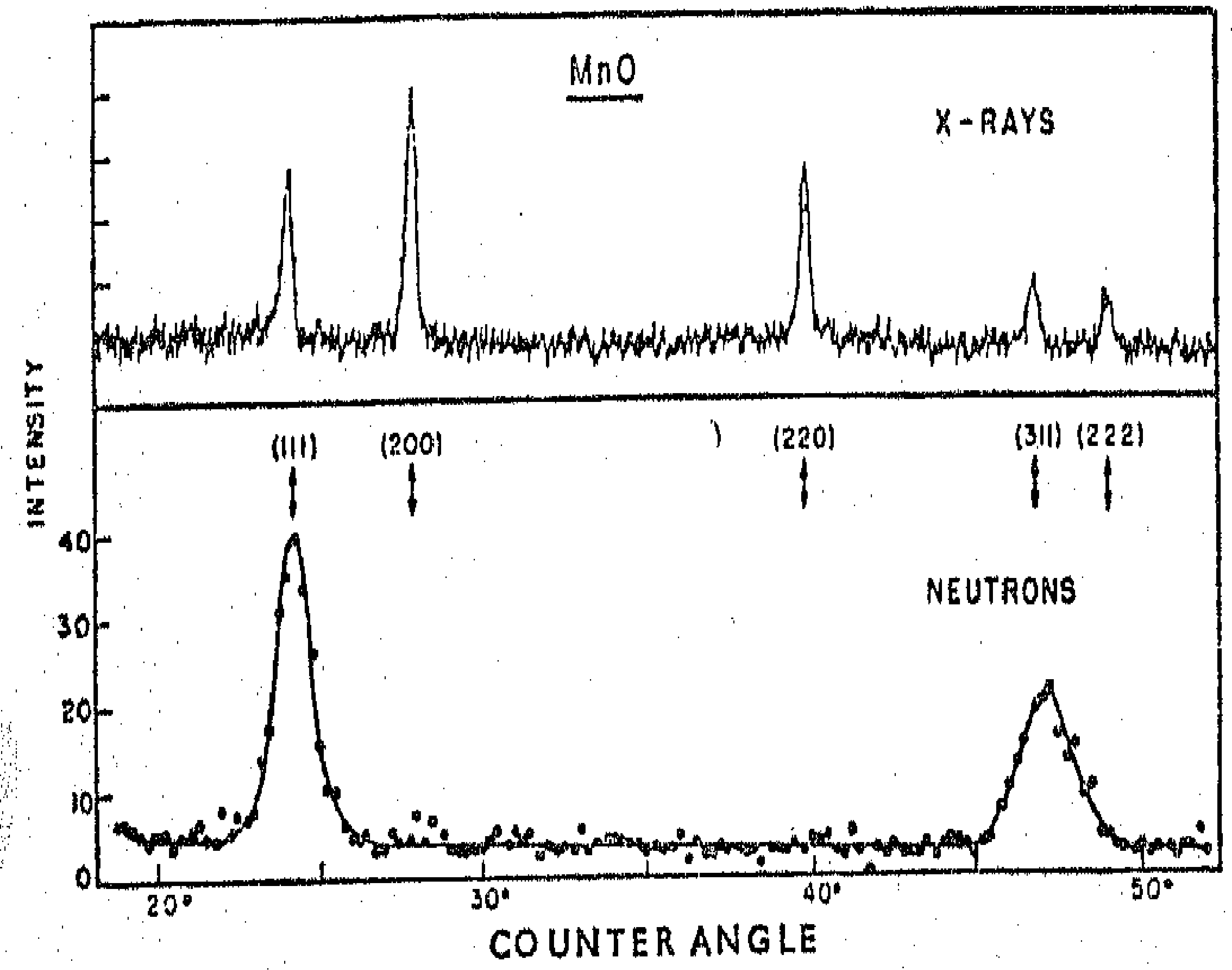


Fig. 15. X-ray and neutron powder diffraction patterns taken with MnO. The pronounced differences are caused by the reversed phase of neutron scattering by Mn nuclei as compared to that by O nuclei. With X-rays, the scattering by the two atoms is of the same phase. (By courtesy of the American Association for the Advancement of Science, from an article by G. G. Shull and E. O. Wollan, 'Science', July 23, 1948.)

The next problem is the useful life of the reactor. Here we require to know the effect of intense neutron irradiation on the pile materials – uranium, graphite, metals. This is the biggest uncertainty in this particular programme. We have not yet enough information to predict the course of events. The third problem is that of refuelling and processing of used nuclear fuel. As the nuclear reaction proceeds, U 235 is turned into radioactive and stable fission products which will absorb neutrons and decrease K. On the other hand U 235 will be replaced in part at least by a secondary fuel, plutonium.

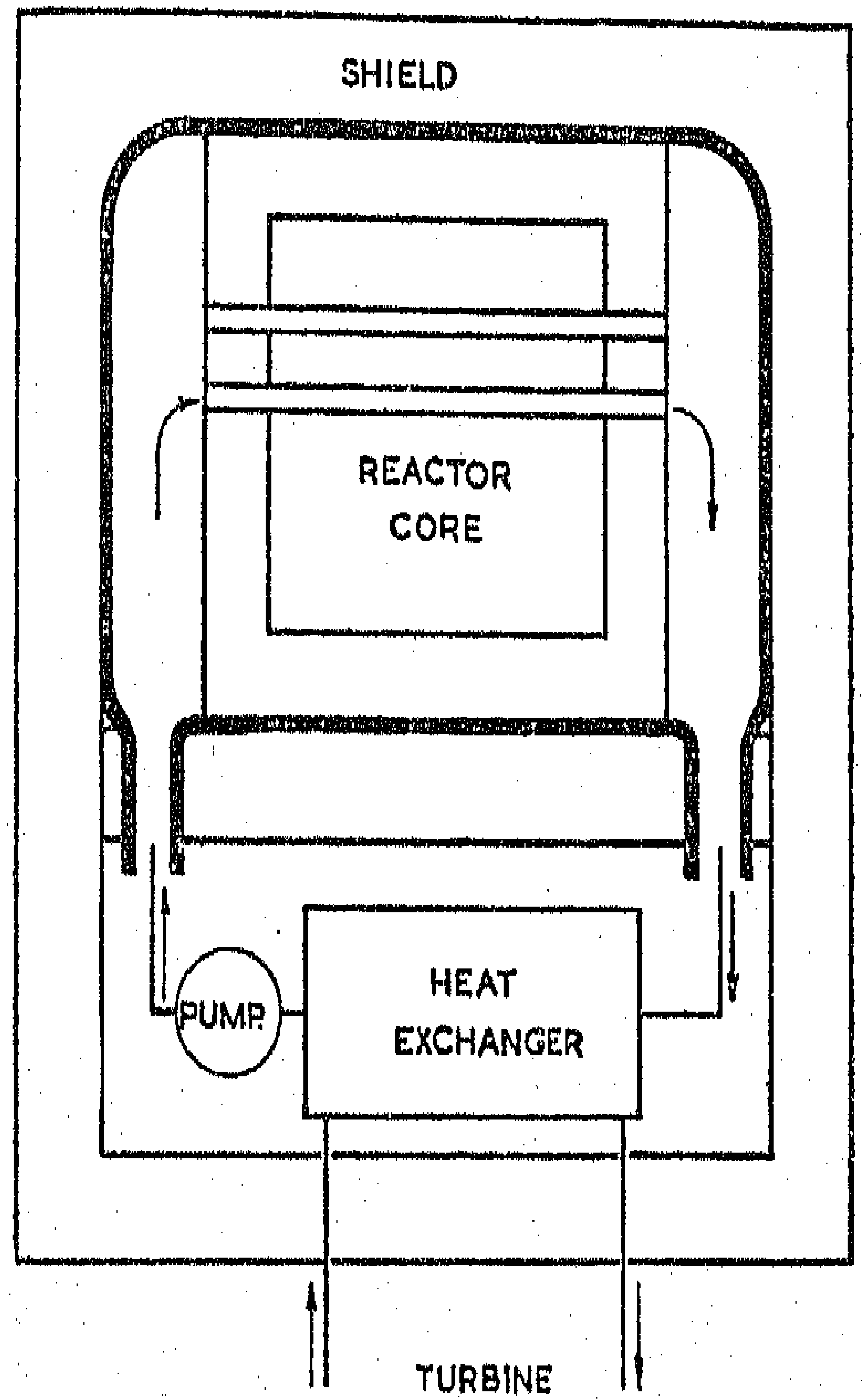


Fig. 16. Circulation of coolant through a pile to produce useful power. (A.E.R.E. copyright.)

This is because neutrons from the fission process are captured in U 238 to produce plutonium by the reaction

$$U^{238}+n \rightarrow Np^{239}+\text{Electron}$$

$$\searrow$$

$$Pu^{239}+\text{Electron}$$

Plutonium is a nuclear fuel with similar properties to U 235. These Pu atoms are in turn destroyed by fission but the surplus neutrons can again produce Pu atoms.

We have therefore a sequence of events in which primary fuel atoms of U 235 are replaced by Pu atoms and some of these are in time replaced by more Pu atoms. This is a process known as 'breeding' of nuclear fuel from the primary fuel U 235.

In principle therefore we could let the reaction proceed until we had obtained appreciably more energy than the fission energy of all the U 235 present.

Suppose we assume that difficulties with materials will allow us to let the reactor run until we have burnt up 1 per cent of the total uranium – 40 per cent more than the U 235 content of the fuel. We can now do some rough arithmetic to estimate fuel consumption. Let us assume we have available 100 tons of uranium a year of which we burn usefully 1 ton. The destruction by fission of 1 ton of uranium is equivalent roughly to the burning of 3 million tons of coal. It would provide 24.10^9 kilowatt-hours of thermal energy, or at 25 per cent efficiency 6.10^9 kilowatt-hours of electrical energy, which is about one sixth of our annual electrical consumption. We should therefore require about 600 tons a year of uranium to provide for the total electrical needs of Great Britain and about twice this to provide a thermal energy, equal to our present total thermal needs. This is a rather large amount measured in terms of world pre-war output. Uranium is, however, present in large quantities in low concentrations, so that the supply problem becomes one for the chemical engineer – to find a means of *economically* upgrading uranium present in low concentrations in rock, shales and commercial ores.*

In this somewhat hypothetical power system I have shelved the important question of degeneration of materials and avoided the problem of reprocessing of fuel by assuming the reactor would run until we had burnt up 1 per cent of the total uranium. We can now make a guess at fuel costs by taking the price which is now being publicly offered for uranium in the form of ore by the U.S.A.E.C. of about £2000 per ton. Our 6.10^9 kilowatt-hours would cost therefore £120,000 for uranium ore, so that the cost per kilowatt-hour will be about 1/200 of a penny. This, however, is a highly illusory figure, for we have now to add the costs of purifying the uranium, turning it into metal and suitably cladding it for insertion in the pile. I am not able to follow this analysis further, but it seems probable that in such a system fuel costs would not be a major contribution to overall power costs. The natural uranium reactor cannot therefore be lightly dismissed as a large-scale power producer, but time is required to show whether the many technological difficulties I have sketched can be solved.

The other lines of development of power-producing reactors require uranium enriched in its U 235 content or a pure nuclear fuel such as plutonium. Uranium enriched in U 235 can be produced by a diffusion plant such as that built at Oak Ridge. The capital cost of this plant was, however, given as 500 million dollars and its running costs as 72 million dollars a year, of which a large part was no doubt made up of electrical power costs. Although the output has not been published, we seem unlikely to build up an economic power system using diffusion plant enrichment as a permanent intermediate step.

The main hopes of an economic nuclear power system rest in fact on a thoroughgoing application of the breeding principle.

If a single neutron producing a fission results in 2+x neutrons being emitted, we can regard one of these neutrons as replacing the original neutron and so carrying on the chain reaction. We have therefore $1+x$ neutrons available for useless absorption, for loss by escape and for the production of new secondary fuel atoms.

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*See page 96.

If δ neutrons are absorbed or lost we are left with

$$1+x-\delta=1+g$$

neutrons to produce secondary fuel atoms.

For each primary fuel atom destroyed we therefore produce $1+g$ secondary fuel atoms where g is the 'gain factor' per cycle.

We can therefore imagine the development of a power system in which we start with a ton of primary fuel. We burn this in a reactor, producing in so doing 24.10^9 kW-hours of thermal energy. At the end of this time we finish up with $(1+g)$ tons for refuelling the original and some new reactors.

The growth of fuel stocks will then depend on the burning time of our nuclear fuel. Since the gain factor will at most be fractional the rate of compound interest is small and we would like to turn over our capital quickly – in the time of a few years.

If we assume a turnover time of T years we must burn our fuel at a heat extraction rate of $\frac{24.10^9}{365\times24\times T}$ kW per ton or about $\frac{2.8}{T}$ kW per gram.

This is quite a high extraction rate if T is only a few years, but this does not seem to be impossible.

Our more serious difficulties will come from the fact that in this system our nuclear fuel will certainly need to be continually processed for removal of the radioactive fission products. These chemical engineering processes are technologically difficult and certainly costly. The very large uncertainty at the moment lies in estimating the cost of the processing. The fuel will have to be removed from the reactor, dissolved in acid, the radioactive products extracted

and the fuel remade into metal or other form suitable for fuel elements. The amount of radioactive products extracted will be very large. The activity at first decays rapidly with time, but the rate of decay then slows down as the shorter-lived products disappear. Ultimately the decay law approximates to a $t^{1.2}$ law so that as the decay time increases from 100 to 1000 days the activity decreases only by a factor of 16.

If we apply published results, a reactor developing 100,000 kilowatts of thermal energy will produce, in each second, radioactive products which 100 days later will have an activity equal to that of 20 grams of radium.

Thus one year's output of radioactive products, allowed to decay for about 100 days, will have an activity corresponding to several tens of millions of grams of radium.

A world run on nuclear power would be faced with the disposal of many times this quantity, bearing in mind that there are no processes other than nuclear by which radioactivity can be destroyed.

If we were to adopt the procedure used for disposal of industrial effluents, dispersing in the sea, and were to disperse it uniformly into the Atlantic Ocean, which has a volume of about 3.10^{23} ccs., we should have roughly 10^9 curies dispersed in this volume, so that we should arrive at a concentration of 10^{-14} to 10^{-15} curies per cc. Now this is already approaching the existing concentration of radioactive materials in the oceans, so that this solution is probably not acceptable, although small quantities of radioactive material can be disposed of in this way without appreciably increasing the existing radioactive content of the ocean.

Concentration followed by storage is another solution – storage in the frozen wastes of the Arctic has been rather fancifully suggested.

Although this prospect is discouraging we are not likely to have to worry about it seriously for ten to twenty years, and time may bring a solution.

The Course of Development

The pattern of development is now becoming somewhat clearer. The U.S.A.E.C. have announced that they are going to build four new types of reactors. One of these will have as its principal use the testing of materials for future reactors; it will therefore have a high intensity of neutron radiation and will be built from uranium highly enriched in U 235. The second reactor will be a pilot reactor to study the possibility of propulsion of naval vessels by nuclear energy. It will be of the slow neutron type, probably using enriched uranium. The third reactor will be a fast neutron reactor intended to explore the potentialities of such reactors as breeders and power producers. The fourth reactor will be an intermediate reactor in which the neutrons are slowed down somewhat but not to the velocities of slow neutrons. These reactors are also potentially interesting as breeders.

They have set aside a large area of desert for this programme and propose to spend 120 million dollars a year on its attainment. Nuclear power is therefore being taken seriously.

Special Applications

The use of nuclear reactors to drive a naval vessel is envisaged in the U.S. programme. One of the limiting factors of a reactor for a mobile power unit is the weight of the shield, which can hardly be reduced below several hundred tons for a reactor power unit developing a few thousand horsepower. This difficulty will seriously handicap applications to the propulsion of aircraft, though the possibility cannot perhaps be completely ruled out in view of the increasing overall weight of aircraft. The U.S. have some time ago announced that they are seriously studying such possibilities. Applications to propulsion of land vehicles are even more improbable. An application to the propulsion of rockets would seem to avoid this difficulty since no shielding would be required. For such purposes a reactor using U highly enriched in U 235 would be required to reduce the weight to feasible values. Such a reactor would be extremely costly, and there are certain to be more important uses for the very limited stocks of such nuclear fuel likely to be available for some time to come. A technical investigation of the possibility has been published in the M.I.T. lectures on the *Science and Engineering of Nuclear Power*.

Conclusion

Nuclear power is at present in a very early development phase, in which some of the problems to be solved have been defined. We require experience by operation of pilot plants before we can say that they can be solved. The pilot plant stage is likely to occupy the next ten years.

The developments after that depend on our experience, on availability of materials and on the world political situation. We can be fairly certain that there will be no large-scale development in the next decade, and it is unlikely that any appreciable part of world power will come from nuclear sources in the following decade, though there may well be special applications of importance. We ought not, therefore, to be diverted from pursuing in parallel the many other methods by which fuel economy can be achieved and world fuel resources increased.

5

Raw Materials for Atomic Power

C. E. TILLEY, F.R.S.

URANIUM is widely distributed in minute amounts in rocks of all kinds, an average figure for the accessible crust being approximately 4 grams per ton. Its abundance is therefore about that of the elements arsenic and beryllium. Taking the earth's crust as a whole, the total amount of uranium to a depth of 10 miles is of the order of 100 million million tons. The element occurs in appreciable amount in a great number and variety of rare minerals, being frequently associated with tantalum and niobium, the rare earth metals, and thorium and vanadium. The chief rock sources of these uranium minerals are (1) pegmatites of granite composition, (2) hydrothermal mineral veins – both products of crystallisation from hot igneous solutions, and (3) sediments.

Hitherto in the recovery of uranium (or radium, present in all uranium minerals, the equilibrium amount being 1 gram radium in 3 tons of uranium) the chief source minerals have been pitchblende (oxide of uranium), carnotite (potassium uranium vanadate), and to a lesser extent torbernite and autunite (copper and calcium-uranium phosphates respectively).

In spite of the comparatively wide distribution of uranium minerals, the mining of the metal has been confined to a few localities.

Pegmatite Sources

Uranium-rich minerals occur as accessory constituents in granite pegmatites and have been recovered in small amounts

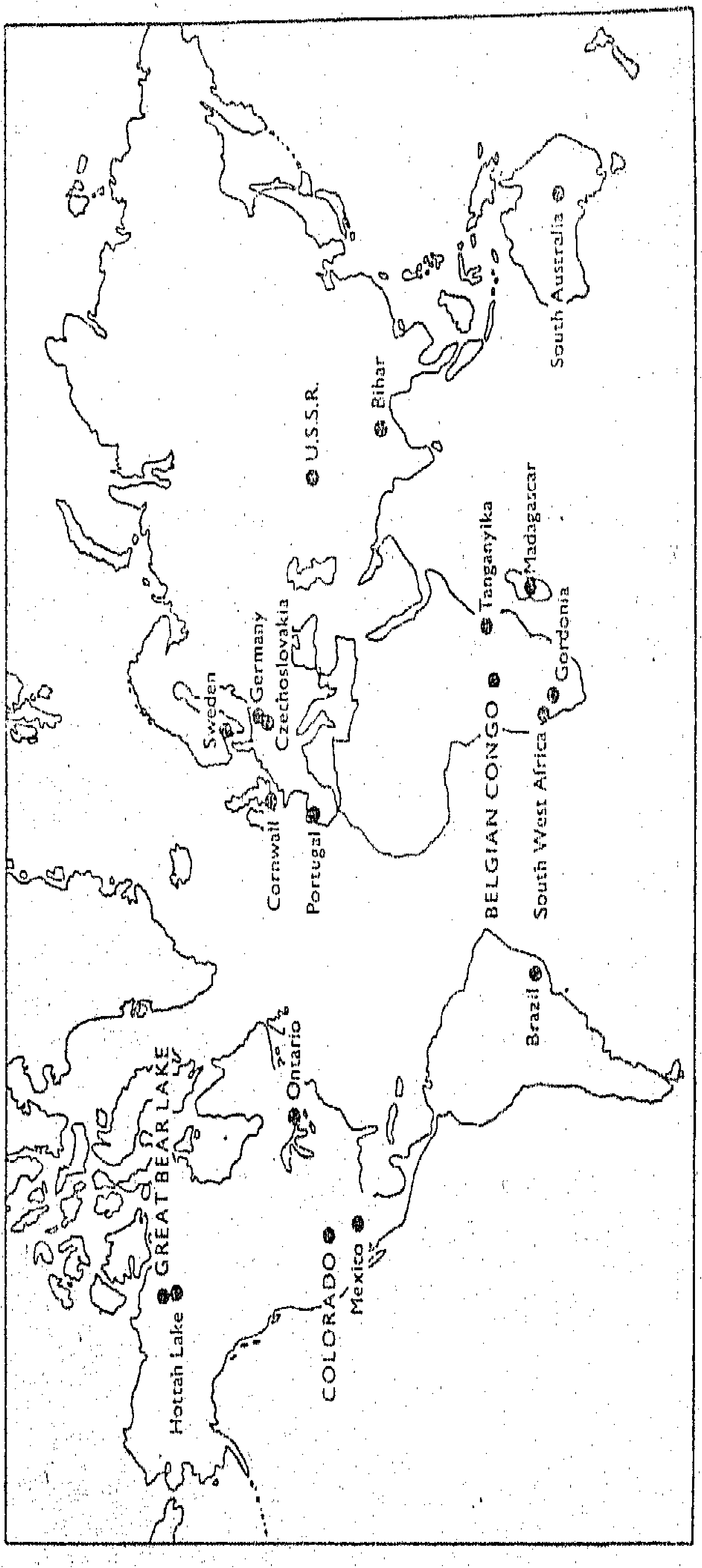

Fig. 17. World distribution of radium-uranium deposits. The chief productive localities are in capital letters.
(By courtesy of the Director, Geological Survey Museum.)

from pegmatite dykes, usually mined for feldspar used in the ceramic trade. The best-known pegmatite areas with dykes carrying occasional uranium minerals are those of the Canadian Shield in Ontario and Quebec, of New England, South Dakota, Texas, Southern Norway, and Madagascar. Similar pegmatite areas are found elsewhere, but the total production of uranium from all such sources could be expected to reach only a small tonnage.

Hydrothermal Mineral Vein Sources

The two principal sources of supply since 1930 have been the pitchblende-bearing deposits of Shinkolobwe in the copper belt of Katanga, Belgian Congo, and the deposits of Great Bear Lake, Arctic Canada. Before the war an agreement had been concluded between Union Minière du Haut Katanga (operating in the Belgian Congo) and Eldorado Gold Mines Ltd (Canada) for marketing radium, whereby the former would supply 60 per cent and the latter 40 per cent of the world requirements. This agreement was later dissolved. The production of uranium in 1939, principally from the Katanga and Great Bear Lake deposits, has been estimated at 1000 tons. To the hydrothermal class of deposits belong the historic mines of Joachimstal (Czechoslovakia), Schneeberg (Saxony), and the formerly worked veins of Cornwall. In Portugal, workable ores have been recovered from veins in the granite districts of the province of Vizeu (east-south-east of Oporto) and in the region between Guarda and Sabugal on the east side of the Sierra d'Estrella. Other deposits are found at Mount Painter (South Australia) and in the district of Sofia (Bulgaria).

Sediment Sources

Knowledge of the sedimentary part of the geochemical cycle of uranium is still meagre, but a frequent association of the element with vanadium and with hydrocarbons is suggestive that biochemical agencies may be in part responsible for its concentration in sediments. Vanadium is known to be present in some sea organisms (e.g. in the blood of certain sea-cucumbers) and it is relatively concentrated in some petroleums, bitumens, and asphalts.

The vanadium association in sediments is realised in the carnotite deposits of south-west Colorado and adjacent areas of Utah, in Fergana (Russian Turkestan), and in the Caucasus. The low-grade ores of Colorado and Utah have been recovered from Jurassic sandstones in which they occur as impregnations sometimes associated with asphalt. These Colorado occurrences at one time provided annually several thousand tons of ore and, before the working of the Katanga ores, the United States produced more than double as much radium as all other sources together. Prior to the war these deposits were, however, of greater importance for their vanadium content than for their uranium.

The hydrocarbon association of uranium in sediments is found in the Kolm of the Cambrian shales of Southern Sweden, a 'coal' yielding an ash containing up to 2 per cent uranium oxide. The investigation of sediments for such zones relatively enriched in uranium will no doubt be guided by biochemical considerations of the kind now noted.

Thorium, like uranium, is also widely distributed in minute amounts in rocks, the average figure being about 10 grams per ton. The richest thorium minerals are the oxide and silicate, which occur as accessory minerals in granite pegmatites, but only a few tons of these minerals have been produced, chiefly from river sands in Ceylon.

Monazite is the chief workable ore of thorium. This mineral is a phosphate of cerium and yttrium earths containing a variable thoria content (1–14 per cent) and it occurs primarily as an accessory constituent of granites and pegmatites. As worked, however, the source is river and beach sands in which the mineral has been more or less concentrated by the sorting action of water. Hitherto the more important use of thorium has been in the manufacture of incandescent gas mantles, and mesothorium was produced from the residues of monazite sand after thorium and cerium had been extracted. Monazite sands have been worked chiefly in India, Ceylon, Brazil, North Carolina, Idaho, and Florida. Other sources are the Netherlands East Indies and New South Wales. Average commercial monazite concentrates yield from 6–10 per cent thoria. The richest known deposits are the sands of Travancore (South India, coast region between Quilon and Cape Comorin), where the reserves are very large.

6

The Physics of the Bomb

P. MORRISON

Nuclear Energy Controlled: The Pile

The Hiroshima explosion signalled to the world that the large-scale release of nuclear energy had been achieved. The spectacular and terrible detonation drew all attention to the catastrophic release of energy which in the bomb had been made possible. Even now that the facts of the matter are known, a belief remains that the 'control' of nuclear energy is still beyond our means. Nothing could be further from the truth: the nuclear chain reaction has operated literally every day from December 2nd, 1942, until now. It has worked in one of the several existing forms of piles, or chain reactors, whether the uncooled pile of graphite blocks and UO_2 lumps which was man's first nuclear reactor, or the huge plutonium-producing units at Hanford, which quietly warm the Columbia River. This is operated with a small reproduction factor so that the number of neutrons produced in a generation of the chain by a single neutron reaches unity *only* after the delayed neutron emission from the fission fragments has occurred. By this means the chain reactor is made into a smooth and trouble-free device. Probably no other machine can be made to operate successfully over such a great range of intensity, and stabilized at any operating power level allowed by the engineering design by the simple motion of a single control element. No complicated moving mechanism or delicate vacuum system forms part of a chain reactor. The steadiness and smoothness are noteworthy; the system is inherently stable. And why not, for the only moving parts are neutrons! At both the

Argonne and the Clinton piles, one minor problem has been to provide a routine of meter-reading and recording exacting enough to ensure that the man who is operating the pile does not find it too easy to fall asleep. The normal demands of keeping the pile intensity constant are so easily met that the operator has very little to do. Starting and stopping the reactor is simply a matter of displacing the control rods by a predetermined amount.

The problem before the whole Manhattan Project, given the production of quantities of fissionable material, was to make the chain reaction uncontrolled and explosive. The Los Alamos laboratory was given this problem, and its practical solution was in almost every detail conceived and executed there. While the scale of the operations at Los Alamos is far smaller than that at the great production plants, the diversity and the difficulty of the research and production there carried out make the site a unique and incredible one. Military security regulations still prohibit the discussion of many of the interesting problems there solved, but following the Smyth report and making obvious extensions of previous knowledge very much of the physics of the bomb can be discussed.

The Meaning of a Microsecond

It was clear from the beginning that the great piles of uranium and moderator could not make satisfactory military weapons. In the first place, they were too large for reasonable means of transport. Even more so, while they are capable of running at any power, and can certainly be so set that the intensity will melt any structure, they cannot violently explode. The rapid rate of energy release is what makes an explosion. In the pile, the balance of neutrons made in the chain against those lost by non-fission capture is too narrow. The gain in number of fissions per generation is small, so that many generations are needed to produce a doubling of the intensity. Even more important, the chain operates on thermal neutrons. Such neutrons move at rifle-bullet speeds, and in travelling the many feet that are required to escape from the pile, they make a large number of collisions and eventually spend a lifetime of a thousandth of a second or so in each generation. Since many generations are needed, the time which would be required for the explosion of a pile may be measured in hundredths of a second. A block-buster explodes in the time it takes for a detonation wave, travelling some five thousand metres per second, to cross the mass. This time is perhaps one hundred microseconds.* The deliberate explosion of a pile would have the character not of a bomb, but perhaps of a steam boiler bursting.

All the criteria for a weapon are satisfied by a very different kind of chain reactor, the kind from which an atomic bomb is actually made. The reactor is not a large and carefully arranged lattice of moderator and natural uranium, but a small compact mass of nearly pure fissionable material. Instead of the tons of even the best pile, the critical mass of a sphere of pure plutonium or highly-enriched U 235 is measured in kilograms. The loss of neutrons to the chain by non-fission capture is nearly zero, so that the reproduction factor is large, much greater than the near-unity value of the pile. Perhaps most important, the chain no longer operates on thermal neutrons. Even the primary fission neutrons have a good chance of producing daughters for the chain. Only a few collisions make up the whole life-history of even an unusually long-lived neutron, and the fast neutrons move not at rifle-bullet velocities, but at velocities many thousands of times greater. A typical fast neutron would travel from Los Alamos to London in a second. A generation, in the small chain reactor which is a bomb, is measured by the time that it takes a fast neutron to travel a few inches. The time is perhaps a hundredth of a microsecond. And the intensity increases markedly in a single generation if we use a mass well above the critical mass.

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*Throughout this chapter we shall find it convenient to measure time in millionths of a second, or microseconds. A high-velocity rifle bullet could cross the letter 'o' in one microsecond.

How many generations are needed for an explosion? We know that the energy released from the fission of a pound of fissionable material is about that resulting from the explosion of eight thousand tons of TNT. The present atomic bomb, which yields the energy of some twenty thousand tons of TNT, must therefore consume a couple of pounds of material. If to every fissioned atom we assign one neutron – the one that did the job – we must have released two grams of neutrons at least in the explosion. But in two grams of neutrons there are about 10^{24} particles. All of these descend from a single neutron which initiates the chain. If we needed, for the sake of example, only one generation to double the intensity, this would mean about seventy-five generations of the complete chain. The whole process would take only a microsecond, and the violence of the true explosion would clearly be present. This is the very opposite of the controlled reaction of the pile. It is worth while noting that the delayed neutrons, which are not even emitted for tenths of seconds after fission, play no part whatever in the explosion of the bomb, though their role is determining in pile operation. The two applications of the nuclear chain are as different as the burning of coal and the detonation of TNT. It is not the least remarkable property of the fission chain that the same mechanism can act in two situations physically so different.

The Chain Starts

From all this it is perfectly clear how to make a bomb. You must bring together enough fissionable material to have more than a critical mass. The more you assemble together, the less the proportionate leakage of neutrons out of the mass, the greater the increase of neutron intensity per generation, and the more rapid the whole process. The trick, of course, is to make the initial assembly. For the

geometrical conditions and the nature of the material alone determine the rate of change of the neutron or fission intensity, and hence the energy release. There is no switch to turn the chain reaction on or off. You must do this by modifying the shape. If you have, say, two pieces of material each weighing nine-tenths of the critical mass there will be no self-sustaining chain until you begin to bring the two pieces together. As they draw close the neutrons which once escaped out of the neighbouring surfaces of the two pieces now have some chance to take part in the chain, because they are captured and induce fissions in the other piece of material. Long before you had caused the two pieces to make contact, the total configuration would have become critical. As the pieces approached even closer the reproduction factor would steadily increase, and the neutron intensity, had a chain started, would grow at an ever-increasing rate. If your actions were slow, the energy released would have melted the pieces long before they had approached contact. Under these circumstances the energy released would not be that of thousands of tons of TNT, but simply that sufficient to melt or otherwise destroy the assembling mechanism. Obviously this will not do. The solution is clear: bring the pieces together rapidly. Assemble them by making one piece the projectile of a small cannon, the other its target, placed directly at the mouth of the cannon. But recall the time scale of the whole phenomenon. Only microseconds are required for a tremendous energy release. Even special artillery will not move our pieces more than a fraction of an inch in this time. It is clear that the movement needed must be of the order of the size of the masses assembled, certainly several inches. There is only one way out of this dilemma. Nothing will happen to our assembling device if the chain does not start until the pieces are assembled.

Let us try to follow in words the incredibly rapid events which make up the nuclear explosion, beginning with the role of chance and ending with the catastrophe that follows.

The Toss of a Coin

All the spectacular effects of the atomic detonation are started by an event as purely chance in its nature as the toss of a coin or the flip of the ball in roulette: the presence of a single neutron. If the neutron appears, by sheer chance, before the assembly has reached the degree of supercriticality which its designers had hoped for, the bomb will fail, though all of its components function exactly as planned. For the first time, perhaps, a single atomic event, a necessarily uncontrolled circumstance, can measurably affect the world of men. Again, if no neutron appeared, though some were expected, the projectile might pass through the target, and the bomb parts fly apart again without detonation. Of course, some ingenious though simple device can be introduced to prevent the fiasco of failing to get started on the chain, the fiasco of post-detonation. Any neutron source – such as a beam of radium alpha-particles arranged to strike a beryllium foil when the position of target and projectile is the best possible one – which can be turned on at the right time, will make it very sure that a neutron is present, by emitting many of them in the time the projectile moves only a short distance. But nothing can save the bomb from *pre*-detonation except chance.

However he may be intrigued by the philosophic implications of the predetonation problem, the designer of the atomic 'gun' must face it realistically, which is to say quantitatively. While he cannot escape pure chance, he may estimate how likely is his failure. He will not worry if after he has finished his design he is willing to wager odds of 100 to 1 that his gun will explode. No military venture has a chance of success much greater than that, neutrons or not. Is this high reliability possible? Let us make a guess at the numbers, using only pre-war information, and not the precise data now available to the workers of the Manhattan District. You will remember that the critical mass of U 235 is measured in kilograms. Such a mass – even if we are pessimistic and take Dr Smyth's upper limit of one hundred

kilograms – will be only about six inches in diameter. The projectile and the target will each be of this size in a possible design. Now when these two active pieces are within say six inches of each other, the neutrons from each piece will find their way with considerable probability to the other. The assembly will be supercritical. If the chain begins, it will build up to a high enough number to destroy the whole device in a few microseconds, as we saw above. The stray neutrons must be kept down. How well must this be done? The projectile in a light naval gun moves six inches in a fraction of a thousandth of a second (a long time in our nuclear scale, some three hundred microseconds). During this time, we should have no neutrons, or at least none to start the chain. It is clear that not all neutrons will start the chain. Some will be absorbed in the steel structure of our gun, some may even produce a fission, but the neutrons from the fission may fail to find the active material again to continue the chain. About the average neutron we can make the sure prediction that it will begin a divergent chain reaction in a supercritical mass; but about a single neutron we must quote only probabilities. But we will leave this out of account, so as to plan for the most difficult case. We shall assume that any neutron appearing in this crucial third of a millisecond can make the bomb fizzle out. We must then require that during that time the wager is a hundred to one against any neutron appearing. Since the neutrons may come at any time taken at random, this is about equivalent to saying that in thirty milliseconds on the average not more than one or two neutrons appear. Where will neutrons come from? The Smyth report lists the sources: (i) cosmic rays, (ii) nuclear reactions in light impurities in the heavy metal, in which the weak alpha rays of uranium may induce neutron emission (analogous to the familiar radium-beryllium neutron-producing reaction), (iii) the release of neutrons by the spontaneous fission of the uranium itself. Let us estimate these stray neutrons. Cosmic rays produce a neutron at the rate of a dozen or so per square foot per second. The impurities, it can be shown by simple calculation, cannot produce even this many if the metal is quite reasonably pure. The spontaneous fission rate is publicly known for normal uranium through work published in 1940 in the *Physical Review* (the chief American physics journal) by two Russian workers, who first observed this queer phenomenon and there described it. Just as uranium spontaneously disintegrates by alpha-particle emission, it spontaneously disintegrates, though very rarely, by fission, without any incoming neutron to cause the event. The rate of such disintegrations is very slow. For every uranium atom which dies by spontaneous fission, tens of millions die by the emission of an alpha particle. The Russian work of 1940 indicates that between five and fifty neutrons will be given off spontaneously by a kilogram of normal uranium in one second. This rare event – so slow and improbable that it would take uranium from ten to a hundred million times the age of the earth to decay by this process alone – is the controlling factor in our problem. We do not know how this rate varies from isotope to isotope; let us assume it is the same for U 235 as for U 238. Then spontaneous fission will produce some five thousand neutrons per second in our bomb, and is by far the chief source of stray neutrons. Our design cannot get the reliability we had hoped. Even if we take some advantage of the fact that not every neutron will start a chain, the chance of pre-detonation by a neutron appearing in the crucial three hundred microseconds is something like even, and not a hundred to one. We have been too pessimistic, of course. For some of the six inches of motion is near the fully assembled position and here the pre-detonation will make very little difference to the final energy release. The problem is after all one of continuous gradation from dud to great explosion, and we have spoken as though it were all or none. But our numbers, guesswork as they are, still show that the controlling factor in bomb design may very well be pre-detonation.

Against this danger there are few measures the designer can take. He can reduce the cosmic ray and impurity neutrons by shielding and by painstaking purification. But their importance is not great. He cannot affect the spontaneous fission rate. To reduce the probability of pre-detonation he may reduce the amount of material in the bomb. When he does this, of course, he reduces the potential energy release. He must use at least a reasonably supercritical total mass. The spontaneous fission rate of the particular isotope which is his active material will thus help determine the size of his bomb: it cannot be too small, or it will not be sufficiently supercritical, nor can it be too large, or the spontaneous fission may cause pre-detonation. Only one thing is at his choice. As the Smyth report says, he may 'reduce the time of assembly to a minimum'. He may shoot the two parts together at great speed. In this way he can cut the chance of a fizzle just in proportion to the amount by which he reduces the time of assembly. The atomic bomb is simple, but its design is not easy!

The Chain is Under Way

Let us trace the explosion still further. By chance and design, let us get projectile fully meshed with target. A neutron initiates the chain reaction. For illustration (we do not know the real numbers) let us assume as we did before that a single neutron may be absorbed, and the resulting fission yields two to take its place. These two each give rise to two, and the chain is under way. In some seventy generations, one neutron has multiplied to a thousand million billion (10^{21}) and enough energy has been released to turn the materials of our bomb into vapour. This is still no nuclear explosion. Only an energy equivalent to that of some ten tons of TNT has been liberated. Everything now depends on the next generations.

If the reaction stops now, the atomic bomb is nothing but a costly and unreliable block buster. But if after seventy successful generations, only ten more can be sustained, the chain will yield the twenty-thousand-ton explosion which devastated Hiroshima. Time is indeed of the essence. As we have said before, the fast neutrons which carry the chain in the bomb require very little time to multiply. The whole of the first seventy generations can take place in about one microsecond, during which a bullet would travel hardly a tenth of an inch, or an explosion in TNT proceed a quarter of an inch further into the mass. And the next tenth of a microsecond will make all the difference between an atomic bomb and an ordinary one.

The Chain Reaction Stops

The nuclear properties of matter are not affected even under the conditions now existing within the bomb. The chain proceeds as usual. It will stop only by exhausting all the fissionable material – in a perfectly efficient bomb, this is the mechanism of the end of the reaction – or by some geometrical change which will alter the supercriticality of the assembly. If the now vaporized bomb expands, its surface will increase, and the chance for a neutron to leak out of the less dense active material into the outside world will grow. When sufficient expansion has taken place, when the chance for neutron leakage has so increased that the chain reaction no longer multiplies the number of neutrons present, the release of nuclear energy has stopped. The bomb reaction is ended. It is clear that if the bomb we have described expanded in all directions a foot or so, its density would have very much reduced. The chance that a neutron could escape from the mass without colliding with a fissionable atom on the way would have increased very much, and the excess of one neutron would probably no longer be enough to sustain the chain. To expand a foot in a tenth of a microsecond implies a motion at a speed of a few thousand miles per second, and an accelerating force corresponding to suddenly created pressures of millions of tons per square inch. It is as though the weight of ten battleships were suddenly

brought to bear one very portion of a surface as big as a sixpence.

It is clear that some expansion will occur. This is in fact what limits the reaction. The details of the physics of this spectacular event will have to wait for later publication. Obviously the strength of solid materials plays no part in this phenomenon. All that matters is the behaviour of the intensely heated gases, their inertia, and the way in which the great blast wave can eat its way through the material of the bomb and the matter surrounding it, pushing out with these great pressures, until the whole device has expanded and the energy release has stopped. The release of energy in the form of the energy of motion of fission fragments, its transformation to heat, at temperatures beyond those of the centres of stars, and the expansion wave of the hot gas are all subjects of importance to the designer of bombs. For the key to the efficiency of a bomb is the speed at which this expansion takes place, compared to the speed at which the last few generations of the chain cause the energy release to multiply. The last tenth of a microsecond is the crisis of the end of the reaction, just as the first three hundred microseconds were the critical time for its initiation. The measure of the difference between nuclear explosive and ordinary cordite is found in this vast change in time scale. Nuclear explosions are fast.

The role of the so-called tamper, a heavy wall of matter placed around the active component of the bomb, is now clear. Such a wall will, of course, act as a cloudy neutron mirror: it will reflect back to the fissionable material some of the neutrons which might otherwise have been lost into space. This will make a given mass of material more supercritical than without the reflector. This is obviously a sought-for result. Even on the controlled piles such neutron reflectors are used. In the bomb they are less advantageous than at first glance appears, because the time that a neutron takes to wander into the tamper and come back to the bomb again will find it arriving long after its birth. By that time the neutrons present in the bomb have multiplied considerably in number, and the inheritance of reflected neutrons from an earlier and neutron-poorer epoch is no longer so important. On the other hand, a simple mechanical property of the tamper is now of great importance. The heavy tamper must be pushed out by the expansion of the heated active material. The blast wave must move into the tamper before expansion can end the reaction. The tamper really does 'tamp' the nuclear explosion, almost as the wooden tamping rod of the miner tamps the dynamite into the drill hole. It increases the pressure required for expansion, delays the final expansion, lengthens the time of the reaction, and hence increases the energy release.

The Expansion: The Ball of Fire and the Mushroom

In a fraction of a microsecond, then, the energy of the bomb has been released. From heat, part of it has become the mechanical energy of the out-rushing material of the tamper. Some fraction of the total is in the form of 'penetrating' radiation – neutrons and gamma-rays – which must be considered later. But just now the interest centres on the hot ionized star-stuff of the exploded bomb. Out the edge moves, until in a few score microseconds the whole mass occupies a sphere something like fifty feet in diameter. When the heavy uranium and steel bomb has been spread as thin as this, it no longer has the density of metal, but that of ordinary air. From this time on the expansion is slower, and the hot material mixes with the air around, by now also heated to an ionizing, beyond-white, heat. The air and the vapour of the bomb continue to mix and the heated mass eats further and further out into the undisturbed air, displacing and heating the layer beyond the edge of the hot sphere. When this hot gas has expanded until the pressure within is not greater than the pressure of the atmosphere it stops growing. Perhaps a millisecond has elapsed. The gas has formed the hot 'ball of fire' which measures many

hundreds of feet in diameter and glows with a white heat for as much as a second or so. It is this hot ball sitting on the desert sand which turned it into the iron-containing friable green glass that carpeted the desert floor in the test explosion called Trinity.

The ball of fire then cools a little, by radiating away its heat. In a short time it begins to rise, like the hot air balloon that it is, and the cool currents rush in around it. It rises, leaving beneath it as it goes a trailing column of dust and cloud. The great column rises, carrying within it the active fission fragments left by the burned material of the bomb. It is incredibly radioactive. For the twenty-thousand-ton-equivalent bomb has within it about a kilogram of fission fragments. The disintegration of this radioactive debris in the first few seconds or minute of its rise represents the activity of a million tons of radium! The fission fragments, of course, are principally short-lived, and in a few hours or a day the far-spread activity has dropped by a very large factor. We who watched at Trinity could see the violet glow of heavily ionized air around the rising column as the material irradiated the upper air.

Everyone has seen the fantastic grandeur of the rising column of heated gases over the ruined cities. Two phenomena of special interest are seen in those fine photographs. The column itself is mainly a cloud, just like any thunderhead, except for the dust and vapour it holds, radioactive and generating heat. The cooler air of the upper air causes the water vapour brought up in the hot column from the air near the ground to condense and the cloud forms. As the column rises like the smoke from a chimney it may come to what is called an inversion by the meteorologists. This is a layer of air warmer, instead of cooler, than the air below it. When such a layer is reached, the gas of the column will spread out and rise no longer. This is the formation of the mushroom. But some of the gas of the column is still being warmed by radioactivity. This gas is warm enough to break through the inversion layer, and the column sends another stem from the first mushroom cap. This too mushrooms, now very high in the air, perhaps six to eight miles. All of these grand and ironically beautiful phenomena can be seen in the moving pictures of the attacks on Hiroshima and Nagasaki.

The Shock Wave: How a City is Flattened

We have left the ground for an account of the relatively lasting spectacle of the mushroom. But a grimmer and more important phenomenon has already taken place below. A large fraction of the energy of the explosion went into pushing aside with extraordinary speed a large mass of air as the ball of fire formed. The pressure wave which pushed aside the tamper as the bomb expanded continues through the ball of fire, and, leaving the ball of fire when the gases stop expanding rapidly, hammers against the undisturbed air with terrible force. This wave is called a shock wave. The physics of the shock wave, which differs only quantitatively in this atomic explosion from the similar wave produced by any explosion, is a subject once overlooked by physics in the main, but forged to a real completeness by the requirements of the war.

A shock wave is simply a sharp sound wave of very great intensity. In a sound wave the pressure increase, followed rapidly by an equivalent decrease, is small in magnitude. But the great compression which the push of the atomic explosion gives to the air not only increases its pressure by a very large factor, but also heats it, as a tyre is heated by rapid pumping. The sound wave so started travels faster than sound in the cool air still unreached by the shock. The shock front penetrates further and further. As it moves it represents a sharp boundary between two regions of air; one region ahead of the shock, yet untouched, still cool and at normal pressure; a second region, hot, compressed, just behind the front, where disturbances travel at high speed in the hot dense air. As the shock front moves it loses some energy by fulfilling its purpose, that is by pushing over anything in its path, but more and more its energy leaks away as heat, by conduction and radiation. The air in the very front of the atomic bomb shock is at first actually red-hot. The shock becomes increasingly less sharp; as it spreads in a great sphere the pressure excess and the temperature rapidly fall, and far away, the disturbance has faded out into an ordinary sound wave, and a rumble is the only evidence of its passage. All the phenomena of sound are associated with the shock wave: it may be reflected, it may leave shadows, it may diffract around obstacles. Such phenomena are responsible for the not quite predictable behaviour of a shock wave passing through the complex pattern of a city. All who have seen the results of an air raid incident will fully appreciate what I mean.

The wave itself is simply a transmission of pressure through the air, successive layers in turn feeling the compression. Behind the compression there follows generally a rarefaction, representing the wake of the original displacement. After the entire wave, both the increase and the decrease of pressure, there comes a real current of air, a wind, which may in such great explosions reach hurricane velocities near the centre, especially in constricted places like buildings.

How is damage done? The high pressures of the shock hammer on the surfaces of buildings. The air inside – ahead of the shock – is, of course, still at ordinary pressures. The difference in pressure represents a force which can break the strongest walls. Through every opening the pressure difference will force a current of air as well, a wind which devastates the interior of most structures lucky enough to withstand the main force of the shock. Here a few figures will make very clear what happens.

At about a thousand feet from the atomic explosion the excess pressure in the shock is as much as ten or fifteen times the normal pressure. This is the pressure needed to cause the death of a man from blast alone, from crushing the walls of the chest and smashing his ribs. At about twelve or fifteen hundred yards the over-pressure has dropped very much indeed. The excess is here only about a third of the normal pressure already present. This seems small, but it is enough to demolish most houses, brick, wood or stone. On an ordinary wall such a pressure difference means a thrust of fifty tons, the weight of a locomotive. Still further out the over-pressure drops more and more. At two miles, it is only a mere 15 per cent of the normal pressure. But this is as much as the effect of a tornado, and will damage structures of any ordinary kind, and demolish the weaker ones. At three miles the effect is down to that of a strong gale, and only light roof tiles, signs, or such weak objects will suffer damage. In Hiroshima we found the first missing roof tiles and broken window panes at eight miles from the blast.

British readers will be impressed by comparable figures for the V-1 explosion: the killing over-pressure is there found only at fifty feet; the demolition pressure at seventy-five yards, and the tornado effects at two hundred yards. The explosions of the atomic bomb are by far the greatest man-made blasts ever observed.

One difference between the blast phenomena in the atomic explosion and those of a block-buster is the duration of the over-pressure, that is, the depth of the strong shock front. The shock from a block-buster passes in a hundredth of a second or so: that from the atomic bomb will generally last many times longer, exerting its force against the structure walls for a longer time, and usually causing more severe damage.

The shock moves at first much faster than sound, but in a rather short distance comes down nearly to the speed of sound in normal air, about a thousand feet per second, or seven hundred and fifty miles an hour. Thus the two or three miles of Hiroshima which saw destruction from blast were flattened in the time it took the shock to cross that distance, perhaps ten or fifteen seconds.

The Heat of the Bomb

We lay on the ground nine miles from the tower in the desert where the first bomb was ready to detonate. The night was cold; the thin air of the high desert just before dawn made us shiver even though it was mid-July. Then came the blinding blue-white flash of the bomb and simultaneously the heat of the noon-day sun full on the face. That great heat out of the cold dawn at ten miles distance is for all of us who were at Base Camp the most deeply remembered experience. The bomb radiates a not negligible fraction of its total energy in infra-red, visible, and ultra-violet light. Its average temperature in the first second or so, when the ball of fire has opened up until there is a sizeable surface to radiate, is like that of the sun, or perhaps somewhat hotter. The effect at ten miles is that of many seconds of solar radiation delivered in a much shorter time. At one mile distance the radiation intensity is one hundred times greater than that we experienced. This terrible flash heat deeply burned most of the men and women in the street within about a mile from the explosion at Hiroshima. Many light cloth and wooden objects – curtains, mats – were set on fire. The flash was so short that no one could move during its main brilliance. As a result the shadow of the nose was sunburned into the skin of many present at the explosion in Hiroshima. We saw a horse with the shadow of a rail fence unburned on his flank, which was elsewhere raw and hairless. This radiant heat is after the blast the most important source of damage. Tens of thousands of dead and injured, and scores of secondary fires can be ascribed to the radiation of the bomb.

Nuclear Effects: Gamma Rays, Neutrons, and the Fission Fragments

For every uranium atom fissioned in the bomb, two fission fragments are produced. By the time the ball of fire has formed, these fragments are no longer screened by the dense matter of the bomb, but only by the dilute vapour of the bomb's debris. Thus the delayed neutrons they emit, and the gamma rays associated with the beta decay of the typical fission fragment, can freely irradiate the outside world.

About one neutron is produced by the fission fragments for every hundred fissions in the bomb. These neutrons spread out in all directions. They are however rather rapidly slowed down and finally absorbed by the nitrogen nuclei of the air, and do not reach any sizeable distance in great number. At Hiroshima Professor Nishina and his staff collected samples of every kind from the region below the bomb. Artificial radioactivity had been induced by neutron capture in many elements. In samples of phosphorus which they prepared from the bones of the many dead whose bodies were recovered within a kilometre of the blast the fifteen-day activity of phosphorus was especially strong. From such measurements they were able to estimate the number of fissions which had taken place. But the amount of neutrons reaching the ground from the height at which the bomb detonated was too small to induce any activity of more than laboratory significance. At the desert test, sodium activity in the salt of the desert floor was strongly excited. It is likely that few persons were injured by the neutrons emerging at Hiroshima or Nagasaki.

This is not true for the gamma rays. They too are emitted from the fission fragments into the air. We normally think of gamma rays as being very penetrating. Compared to the neutrons, this is true. But compared to visible light, gamma rays cannot pass through very thick layers of air. The energy of gammas is so much larger than the binding energies of electrons in atoms that every atom looks much like any other atom to a gamma ray. Ordinary light on the other hand finds air transparent, metal totally opaque. But to gamma rays air or earth offer the same barrier, weight for weight. Now, a thousand yards in air corresponds in mass to about one yard in water, or two feet in earth. Two feet of earth represent a rather heavy shield for gamma rays, and a few thousand yards, if you remember the added effect of

the inverse square law as the distance increases, is a formidable shield, better than that installed at Hanford. Let us make a small computation. Suppose that two or three gamma rays are emitted for every one hundred fissions (as with delayed neutrons) in the seconds that it takes to produce the ball of fire. This represents more than 10^{23} gamma rays. At one kilometre, neglecting the effect of the absorption of the air, about 10^{12} gamma rays strike every square centimetre. The air shielding is small at this distance – perhaps as much as a factor of ten, but not more – and the actual irradiation would be about that which physicians estimate as a minimum lethal dose. Many persons at even larger distances at Hiroshima and Nagasaki died from gamma radiation. Three thousand yards further, however, the dose received would be down by a factor of nine from the inverse square effect of distance alone, and by about a thousand from the six feet of earth equivalent which the additional air represents. So at two miles distance there can be no noticeable effect of the gamma rays from the explosion.

Some of the fission fragments may be blown into the ground. At the test shot, Trinity, the bomb exploded only a hundred or so feet above the surface on a steel tower. The ball of fire containing the vaporised fission fragments rested on the desert sands. A portion of these active atoms became fixed in the glassy slag which was the imprint of the ball of fire. This material remained on the ground, and did not rise when the ball of fire drifted into the air. The region of the crater thus was made very radioactive. Early entry into this area was possible only in the lead-lined Sherman tanks which rumbled in the first two hours into the centre of the crater. The short-lived fission products gradually decayed. About a month after the explosion, the activity was down by a factor of hundreds from the activity observed when the tanks made their initial survey. A party of reporters toured the central region. But even then the ground was active, and no one would have liked to make camp at that blasted spot. The collecting of active samples of the green glass, which has become tacitly named 'trinitite', is still possible. The piece on my desk will still drive the counting dial of a Geiger-Muller detector set at staccato speed.

At Hiroshima and Nagasaki, the bomb was detonated high in the air. This was done both to enhance the energy of the shock wave, by taking advantage of a reflected shock from the surface of the ground, and to lessen the radioactive contamination of the earth. The ball of fire did not touch the ground. Very little of the fission fragments reached the ground, and no dangerous activity was observed at any time. No casualties were caused in these cities by early entry into the region of the explosion.

As the cloud and the mushroom drift across the countryside, the fission fragments they hold will in part condense out on to dust or water droplets, and the activity will gradually shower down on to the surface of the earth far below. The details of this phenomenon are strongly dependent on the weather: a hard rain through the active cloud in the first few hours would deluge the surface with dangerously active water. As time passes, the activity decreases and the cloud spreads; the danger from the contamination lessens. The direct gamma radiation is well shielded by the few miles of air between the surface and the cloud high above the inversion layers. Only if the atoms of the fragments are brought closer to the earth, as by actually falling upon it, is there any sizeable irradiation of the surface. About twenty or thirty miles from Trinity there is a mesa a couple of miles wide and ten miles long on to which a rather considerable activity fell. The New Mexico range cattle which were grazing there developed very noticeable loss of hair, greyness, and even ulcerated sores on their backs. It is dry in that country; the cattle received the dust from the cloud, and it remained for weeks on their backs, close to the skin, representing a serious though not fatal local dosage of radiation. The beta rays from the active material in contact with the hide of the animals much increased the effect.

A thousand miles away from Trinity, in Illinois, the cornfields lay in the hot sun and strong rains of the Midwestern summer. The corn straw from certain of these fields is used for manufacturing the paper in which some sensitive photographic film is wrapped for sale. The batches of paper prepared from corn harvested a week or two after the test shot proved inacceptable to the film manufacturers; it contained enough radioactive contamination to fog some of the film. A physicist testing some Geiger counters in Maryland, two thousand miles from the test shot, noted an inexplicable increase in the background activity of his instruments on July 19th, which went away a few days later. Only when the news of the bomb over Japan was released did he see a reason, which he transmitted to the *Physical Review*. Local rains may have brought down some material from the dilute cloud passing over Maryland in the stratosphere winds. While there is no definite proof that either of these remote events were direct consequences of the first bomb explosion, their timing is most suggestive. It must be said that even more remote effects are not absurd. There are some 10^{24} active atoms of fission produced in the explosion. Weeks afterwards, there are still 10^{18} atoms decaying per second. If these atoms had been uniformly mixed by the winds over a belt a hundred miles long, thousands of miles wide, and the full height of the atmosphere – which certainly overestimates the dilution – the resulting activity would still be conspicuous on an ordinary Geiger counter.

Recent Tests and Their Results

Since the end of the war, five atomic bombs have been exploded in tests carried out by various agencies of the United States. These tests were all made in the remote and once serene coral atolls of the tropical Western Pacific ocean. The first two explosions were made as the world knows in the summer of 1946 in the lagoon of Bikini atoll, where the most costly and surely the most publicised of naval and military exhibitions was staged around the test. The second group of three explosions took place on another atoll, Eniwetok, in the spring of 1948. The American Atomic Energy Commission, the quasi-civilian agency now responsible for the whole field of fission energy in the United States, has established a permanent proving-ground in Eniwetok, and undoubtedly plans to conduct tests there whenever its bomb designers or its military advisers believe they are needed. It is interesting to see from this decision that even the empty desert of New Mexico is too populous to support a bomb explosion without the risk of complaint from the neighbours! The cattle growers of even that arid range want no more irradiated steers.

The results of the tests have not been made public in detail. But the Bikini tests did reveal how great is the force of the shock wave, how enormous the heat of the bomb. The first air burst at Bikini added very little new information, either for the experts or for the informed public observer. It was rather like the three previous air bursts, with the added complication coming from the aeroplane delivery to an anchored target fleet. The scorched and battered ships were reminiscent of the strongest buildings of the Japanese cities. But the second burst was different. Here the bomb exploded somewhere near the bottom of the lagoon. Its energy vaporised a great mass of water, and the expanding shock and the moving gases lifted millions of tons of seawater high in the air, in a giant hemisphere of froth and steam and fission fragments. The tremendous fountain which thus grew up and fell back on to the ships and the whole lagoon has been wonderfully photographed. The scale of the bomb's effect has never been made so graphic as by the sight of the tiny splinters which are battleships shadowed against the enormous column.

The shock wave travelled through the damp summer air above the lagoon, and the rarefaction which followed it suddenly expanded the air, causing the water vapour to condense into cloud. In this way a cloud shot out in a great dome over the whole explosion, to last a few seconds until it warmed. Then the great column was seen: ten million tons of water mixed with many times its volume of air. The fountain rose nearly a mile, and fell back in a great torrent, lasting minutes. Waves spread out from the base of the column, beginning a hundred feet high, and reaching the reef around the lagoon as rather modest breakers.

The physics of the moving of water is more complex – and more spectacular – than that of air, but rather accurate predictions had been made about the exact nature of the events. The air shock was of course muffled by the mass of water, and the bomb's heat spent in the depths of the lagoon. But the swamping deluge of the fountain was the evidence of the bomb's power. Moreover, the flash of radiation – fast neutrons and gammas – was screened off by the wall of water. But the fission fragments, trapped and cooled in the sea, did not disperse in the atmosphere, but went for the most part down to the lagoon as the jet fell. They covered the ships, and their radiations still many months later made work on the decks unsafe. Only scraping off the paint seemed adequate to remove radioactive fission fragments from the decks. One by one the ships which escaped great damage to structure but which felt the full rush of contaminated water have been towed out of the harbour where they were studied for scuttling in the deep sea.

The Eniwetok tests are still essentially secret, but they were pretty clearly tests aimed at studying the design and behaviour of bombs, not tests in which new sites of explosion or new physical effects were examined. The bombs are 'improved', it is said. Again, rather evidently, this means only in detail, and not in principle.

The test explosions* made very clear that the atomic bomb is a flexible weapon which can be used tactically in many ways, bursting in the air, in water, or presumably even underground. A general knowledge of the phenomena we have described makes rather obvious how its military effects vary with the physical circumstances of explosion. Heat, mechanical motion, prompt radiation, persistent radioactive fragments – these are the consequence of the explosion. What they mean to the men and women of the target is complex, variable and uncertain, but it is no mystery. No one can desire that this piece of damage assessment is ever done.

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*Another test of an atomic bomb took place in the late summer of 1949 within the Soviet Union, but first announcement was made by the President of the United States, presumably informed through intelligence and by detection of upper-atmosphere radioactive dust. The atomic bomb is now possessed by the two greatest Powers.

Very recently public announcement has been made of the decision of the United States government to attempt construction of a 'hydrogen'

The Death of a City

In all that has gone before we have described the physics of the atomic bomb. But the bomb did not seem like an experiment in physics when we walked through the long half-ruined shed of the rail station at Hiroshima and saw the litters of the blackened wounded and dying. The bomb is a weapon: the most deadly and terrible weapon yet devised. Against any city in the world from New York and London to the hundreds of large towns like Hiroshima and Nagasaki, the bomb is a threat. In any of man's cities a strike from a single atomic bomb will claim some hundred thousand deaths and some square miles of blackened ruin. The shock wave will wreck brick as it does wood, the gamma rays will kill men with white skin as it does those who have a yellow pigment, the fire will burn the cotton clothing of Manchester

manufacture as well as it did that of Kyoto. And the bombs, if they come again, will not come in ones or twos, but in hundreds or thousands. Their coming will wreck not cities, but whole nations.

Physicists have learned to say more than physics these days. I hope the reader will see the propriety of ending this partial account of the work of the great laboratory at Los Alamos with a few sentences from a speech of its war-time director, Robert Oppenheimer:

'... If atomic bombs are to be added as new weapons to the arsenals of a warring world, or to the arsenals of nations preparing for war, then the time will come when mankind will curse the names of Los Alamos and of Hiroshima.

'The peoples of this world must unite, or they will perish. This war, that has ravaged so much of the earth, has written these words. The atomic bomb has spelled them out for all men to understand. Other men have spoken them, in other times, of other wars, of other weapons. They have not prevailed. There are some, misled by a false sense of human history, who hold that they will not prevail to-day. It is not for us to believe that. By our works we are committed, to a world united, before this common peril, in law, and in humanity.'

bomb. Such a bomb, though it may be initiated by the high temperatures found in the exploding fission bomb, does not itself have any connection with the properties of uranium. It is a thermonuclear bomb, in which energy is released by the nuclear reactions induced by the collisions of charged light nuclei at high temperature. Its time-scale is necessarily explosive; no controlled thermonuclear reaction can exist on earth. Its effects are like those of the fission bomb, only scaled up by a factor perhaps as great as that which exists between the fission bomb and ordinary cordite. If this bomb is ever made, it will represent what is called by some 'an improvement in principle'. (February 1950.)

7

The Use of Radioactive Isotopes in Biology and Industry

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Fundamentals

As is well known, the nucleus of the atom is believed to consist of protons and neutrons, and to contain substantially the entire weight of the atom. The chemistry of an atom on the other hand depends only on the electrons which are present round the nucleus, and in fact only the outermost few electrons are involved in chemical reactions. The nucleus is very small compared with the diameter of the whole atom and the chemical behaviour is therefore concerned only with electrons which are relatively distant from the nucleus and practically unaffected by it.

Since the atom is electrically neutral, the number of planetary electrons must be equal to the number of protons in the nucleus. This number of protons is denoted by 'Z' and is called the atomic number of the atom. All atoms which have the same atomic number will have the same chemistry.

The number of neutrons which will combine with a given number of protons to form a nucleus varies somewhat, so that it is possible to have several kinds of nuclei of different weights, all of them being nuclei of the same Z and therefore of the same chemical element. For example, the atomic number of carbon is 6 and carbon nuclei exist in five different forms:

Carbon-10	..	6 protons+4 neutrons
Carbon-11	..	6 protons+5 neutrons
Carbon-12	..	6 protons+6 neutrons
Carbon-13	..	6 protons+7 neutrons
Carbon-14	..	6 protons+8 neutrons

Atoms of the same element which have different nuclear masses are called isotopes of that element.

The presence of an excess or deficiency of neutrons compared with the normal ratio will alter the nuclear properties of the element, even though there is no effect on the chemical properties, and if the unbalance is sufficient, the nucleus will become unstable, and will emit radiation in returning to a stable configuration. In the case of carbon nuclei, only carbon-12 and -13 are stable. Carbon-10 and -11 have relatively too few neutrons and so emit positrons and become boron-10 and boron-11 respectively. Carbon-14, on the other hand, has too many neutrons for stability, and emits electrons to form the stable nitrogen-14.*

Unstable nuclei, which are radioactive, are characterised by the type and energies of radiation which they emit, and by their half-life, i.e. the length of time in which half the nuclei originally present will have decayed (see p. 190). These characteristics are peculiar to individual types of nuclei, and

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*[Both positrons (*positively* charged electrons) and electrons (negative charge) are emitted from the nuclei of atoms, although they are not thought to be there as pre-existent entities: it is rather as if a proton could turn into a neutron by throwing off its electric charge as a separate particle, the positron; or a neutron resolve itself into a proton and an electron.

For describing these nuclear reactions by the shorthand of equations it is usual to write the symbol for the element with its atomic weight (i.e. its total number of protons and neutrons per nucleus) as an index either before or after and above the line, and its atomic number preceding but below the line. Thus the Carbon reactions may be written as

$$ {}^{10}_{6}\mathrm{C} \text{ or } {}_{6}\mathrm{C}^{10} \longrightarrow {}_{5}\mathrm{B}^{10} + \beta^{+} \text{ (positron)} $$

$$ {}_{6}\mathrm{C}^{11} \longrightarrow {}_{5}\mathrm{B}^{11} + \beta^{+} $$

$$ {}_{6}\mathrm{C}^{14} \longrightarrow {}_{7}\mathrm{N}^{14} + \beta^{-} \text{ (electron)} $$

The n,γ reaction (see page 128) is written

$$ {}_{11}\mathrm{Na}^{23} + {}_{0}\mathrm{n}^{1} \longrightarrow {}_{11}\mathrm{Na}^{24} + \gamma $$

and the n,p reaction is

$$ {}_{16}\mathrm{S}^{32} + {}_{0}\mathrm{n}^{1} \longrightarrow {}_{15}\mathrm{P}^{32} + {}_{1}\mathrm{H}^{1} $$

Ed.]

are not influenced by any physical or chemical treatment, such as heating or freezing. It is because of these characteristics that radioactive nuclei are of such importance.

Production

Before discussing their use, it is desirable to consider the way in which radioactive isotopes are produced and detected. When any nucleus is subjected to bombardment by nuclear particles – a term which includes neutrons, protons, deuterons, alpha particles, and even gamma rays – there is a possibility that a reaction may occur with the formation of a different nucleus. Nowadays, there are tremendous numbers of neutrons available in nuclear piles, and the majority of radioactive isotopes are produced in these piles. In most cases, a stable nucleus captures a neutron, emits some energy as a gamma ray, and becomes unstable. This is referred to as an n,γ reaction. Two examples in frequent use are sodium-24, which is produced from the normal sodium-23, and gold-198, which is produced from gold-197, though there are many others. In these cases, the required radioactive nucleus is mixed with a much greater number of the original stable nuclei, from which it cannot be separated chemically, and the resulting sample may have too low a specific activity (activity per unit weight) to be useful for certain experimental purposes.

If this is so, two other processes may be used. It is sometimes possible for a nucleus to capture a fast neutron and emit a proton instead of a gamma ray (the n,p process for short). This means that the resulting new nucleus has a nuclear charge one unit less than the original, and has therefore chemical properties which differ from those of the parent substance, so that the product can be chemically separated and prepared in a form which has a very high specific activity. Two examples of this process are the production of phosphorus-32 from sulphur-32, and of sulphur-35 from chlorine-35.

A second process is used in the case of radioactive

iodine-131, which is prepared from tellurium. Tellurium-130 absorbs a neutron to become tellurium-131, which then decays rapidly and loses a negative charge to form iodine-131, which may again be chemically separated from the parent tellurium.

An entirely different method of concentrating active material is due to Szilard and Chalmers, and was first applied to radioactive iodine. An organic compound, such as bromoform ($CHBr_3$) mixed with a very small quantity of free bromine is irradiated with neutrons. When the bromine in the bromoform captures a neutron, the recoil of the atom from the gamma ray subsequently emitted is sufficient to break the chemical bond by which the bromine atom had been held. Its place in the bromoform molecule is usually taken by one of the elementary bromine atoms in the mixture, and the active bromine atoms are, in this way, largely concentrated in the free bromine.

So far we have considered only the preparation of active elements, but for many purposes the chemical combination in which the element appears is also important. From the mechanism of the Szilard-Chalmers reaction it is clear that an atom undergoing a nuclear-reaction will be torn from its position in a molecule by recoil from the emitted particle or gamma ray. Thus it is useless to irradiate, for example, a phosphorus-containing compound and hope that all the phosphorus-31 atoms which are converted to radioactive phosphorus-32 atoms by the n,γ process will remain in the same chemical combination in which they were originally. In fact in the irradiation of a phosphate, only about half the active atoms appear in the chemical form of phosphate. The other half appear as phosphite. In general, therefore, it is necessary first to prepare the radioactive element in a definite chemical form and then to synthesise it into the required compound.

Of the radio-isotopes regularly produced in atomic piles, five of the most important are iodine-131, phosphorus-32, sulphur-35, carbon-14 and sodium-24.

Iodine-131 has a half-life of 8 days and decays with the emission of β- and γ-rays, which present no difficulties in measurement. It can now be prepared free of inactive iodine carrier, either as a product of uranium fission, or as has already been pointed out, by the n,γ process on tellurium, forming tellurium-131 which decays rapidly to iodine-131. It is made available in the chemical form of an iodide.

Phosphorus-32 is a radio-isotope of almost ideal nuclear properties for many purposes. It emits only β-rays of high maximum energy and has a half-life of 14.3 days. It can be prepared in the atomic pile either by the n,γ process on ordinary phosphorus-31, in which case the specific activity is low, or it can be prepared by the n,p process on sulphur-32 when the product is carrier free. Phosphorus-32 is usually supplied in the chemical form of orthophosphate.

Sulphur-35, of half-life 87 days, is prepared by the n,p process on chlorine-35. It decays with the emission of β-particles only, these being of very low maximum energy and requiring special techniques for measurement.

Carbon-14 is prepared by the n,p process on nitrogen-14, the material irradiated being generally a nitrate. The C^{14} comes off mostly in the chemical form of carbon dioxide and is made available as barium carbonate of whose carbon atoms about 4 per cent are C^{14} and the remainder ordinary inactive carbon. The half-life is about 6000 years and the maximum energy of the β-particles emitted is nearly the same as that of those from sulphur-35. Carbon-14 therefore also requires special techniques for its assay.

Sodium-24 is prepared by the n,γ process on sodium-23, generally in the form of sodium chloride. Its half-life is 14.8 hours, and a beta particle of maximum energy 1.4 MeV is emitted in cascade with 2 gamma rays of 1.38 and 2.76 MeV energy. The sodium is, therefore, extremely easy to detect, having both an energetic beta ray and an extremely penetrating gamma ray. Sodium chloride is one of the very few compounds which is made radioactive in the required manner simply by neutron irradiation in the pile, without further chemical processing. The crystal consists of a lattice of sodium ions and chloride ions. When it is irradiated with neutrons, activity is produced in both the sodium and chlorine. The chlorine-38 activity decays rapidly, leaving the compound with radiosodium in it. When a sodium-23 ion becomes sodium-24 by the n,γ process it is torn from its original position in the crystal by recoil from the γ-ray, but it remains a sodium ion. Thus when the crystal is dissolved in water, the solution consists of the usual mixture of sodium and chloride ions, except that some of the sodium is now 'labelled' as radioactive sodium-24.

In addition to those elements which can be prepared in the pile, there are a number which can be prepared by irradiation with energetic particles from a cyclotron or similar machine. Many of the cyclotron-produced radioisotopes are unobtainable in the atomic pile and have nuclear properties which make them more desirable for particular purposes. Examples of these are: sodium-22, which is important because of its half-life of 3 years compared with 14.8 hours for sodium-24; iron-55 which has a half-life of 4 years as compared with iron-59 (47 days), and which is also easily distinguished from it by the nature of its radiations, and carbon-11 which has a half-life of 20 minutes, compared with about 6000 years for carbon-14. This group is not as important as that discussed first.

Detection and Measurement (see also pp. 160–193)

It has been indicated that radioactive atoms can be detected by the radiations they emit. The characteristic property of the substances which we are going to discuss is in general the emission of energetic electrons which are called beta rays. The ejection of an electron may, however, be accompanied by further radiation. It happens frequently that, after the electron has escaped, the nucleus remains in an excited state, containing an excess of energy, of which it then rids itself by emitting a gamma ray which is of the same nature as an X-ray, but more penetrating. The penetrating power of γ-rays increases with increasing energy. The same is true about beta rays, but on the whole, beta rays are much more easily absorbed than gamma rays. About two inches of aluminium are needed to cut down the intensity of a beam of gamma rays of average energy by one-half. Complete absorption can be obtained for beta rays of average energy by thirty times less aluminium. Low-energy beta rays are absorbed in exceedingly thin layers of matter, and this makes the detection of some radioactive materials difficult because special care is needed to get the radiation into the detecting device.

Most detecting devices depend on the phenomenon of ionization of gases. If a beta ray enters a vessel containing a gas, it immediately begins to share its energy with the atoms or molecules of the gas by collision. Usually the amount of energy given to the gas molecule is sufficient to rip off one of its outer electrons, leaving the residue of the molecule with an excess positive charge. The process of separating the gas molecule into oppositely charged particles is called ionization; the free electron and the positively charged residue together constitute an ion pair. The more energy the beta ray has, the more ions it can produce. Gamma rays ionize the gas for the most part indirectly, first colliding with an electron, imparting to it a considerable amount of energy and leaving the electron to behave as a beta ray does.

When an electric field is applied to a gas in which ion pairs are present, the negative ions move towards the positive pole and the positive ions to the negative, thus setting up an electric current in the gas. When the electric field is high enough to ensure that all the ions formed in the gas reach the electrodes without either recombining or multiplying, the magnitude of the current is a measure of the number of beta rays per second passing into the gas and therefore the activity of a given sample of radioactive material.

Ionization current as a measure of the strength of a source

is used in electroscopes and ionization chambers. Gold leaf electroscopes were among the instruments first used for radioactive measurement, the discharge rate of the electroscope being proportional to source strength. Modern electroscopes are made with a fine, gold-plated quartz fibre replacing the gold leaf, and these are robust and sensitive. The ionization chamber consists of a closed vessel containing gas in the centre of which is mounted an electrode insulated from the conducting outer walls of the chamber. A potential is applied between the electrode and the outer wall, sufficient to collect all ions which are formed in the chamber, and so to set up the current from electrode to outer wall. With suitable current-measuring devices, a current of 10^{-12} amp. which corresponds to 10^7 ions formed per second, can readily be measured.

Probably the most versatile and certainly the most popular instrument for measuring radioactivity is the Geiger-Muller or G-M counter. This consists of a cylinder made of conducting material. Stretched along the axis of the cylinder is a fine wire. The counter tube is first evacuated and then filled with gas at a pressure of about 10 centimetres of mercury. A good gas mixture has been found to be 90 per cent argon and 10 per cent ethyl alcohol. An electric potential of about a thousand volts is applied between the cylinder and the wire, making the wire positive. This potential is so low that in the absence of ions no current flows. When a beta ray enters the counter, it starts to ionize the gas and the positive ions move toward the cylinder wall, the electrons to the positive wire. These electrons are accelerated by the electric potential and ionize further gas particles. In this way avalanches of electrons are produced. This discharge must be stopped either electronically or by a 'quenching agent' so that the counter again becomes sensitive before the arrival of the next beta ray. The whole process of discharge and recovery takes approximately one ten-thousandth of a second. The precise mechanism of G-M counter operation and particularly the mechanism of the chemical quenching agent are still not known with certainty.

The current pulse developed may be fed through an electronic device to amplify it and thence to a mechanical or electronic recording apparatus. The energy obtained from a G-M tube is not the energy of the particle which enters but is drawn from the energy stored in the high voltage supply of the counter. The particle merely serves to trigger the sudden release of this energy.

Owing to the different nature of beta and gamma rays their detection presents somewhat different problems. Gamma rays will easily penetrate the walls of the counter, but once inside they will lose energy to the gas at a correspondingly low rate. Therefore only about one out of a hundred gamma quanta passing through the counter will be recorded. On the other hand beta rays produce ions inside the counter more copiously and nearly every one of them is counted; but it is more difficult to let them enter. Beta counters are made with thin walls or provided with a thin window (usually of aluminium foil or mica) with a thickness of the order of a thousandth of an inch. In some cases where no gamma rays are emitted and the betas have low energy, the usual windows which can be constructed will absorb a very high proportion of the radiation which would otherwise enter the counter. In such cases it is possible, for instance in the case of carbon-14, to introduce a compound containing the radioactive element actually into the counter itself, avoiding the need for a window.

Radioactive atoms are not the only ones which can be or have been used as marked atoms or tracers in research. Other rare isotopes like heavy hydrogen (hydrogen-2, with a nucleus consisting of a neutron and a proton) or carbon-13 (nucleus consisting of six protons and seven neutrons) have been used, particularly in biological work. In the case of oxygen and nitrogen the stable isotopes oxygen-18 and nitrogen-15 are used, since all the radioactive isotopes of oxygen and nitrogen have very short half-lives. In all these cases the detection of the marked atoms is a more elaborate

process, demanding the use of a mass spectrometer. If one wishes to detect radioactive isotopes the only apparatus needed is a counter and an amplifier system. This apparatus is in principle not much more complicated than a common radio set, and there is little doubt that in due time it will become both cheap and readily available.

A further method used for the detection of radiation takes advantage of the ionization produced in a photographic emulsion. This ionization produces a latent blackening in the emulsion, which can be developed in the same way as in normal photography. This process does not, of course, give an immediate indication of the radiation level at a given spot, but it is most valuable in determining the total amount of radiation received at that position in a given time. For this reason, small dental X-ray films are worn by those who work with radioactive substances and are developed weekly. Examination of the degree of blackening of the film makes it possible to know and record the total radiation to which the worker has been exposed that week.

The photographic detection of radiation is of value in the study of the distribution of activity in a surface or a thin section of tissue, and this is done by placing the emulsion in contact with a section of tissue or material containing the radioactivity. After development, the distribution of radioactive material shown by the blackening can be compared with the structure of the sample shown by normal staining methods in the case of tissue sections, or by etching the surface of metal specimens. This technique of radioautography has been developed until the distribution of activity can be studied in minute microscopic detail.

Medical and Biological Uses

Radioactive isotopes are used in the fields of biochemistry and medicine chiefly to follow where they go in a chemical system or a living body, and also certain of them are useful for destroying tissue in cases where surgery is precluded.

Cobalt-60 can be made in the atomic pile and it emits gamma rays of similar energy to those from radium. Cobalt-60 can therefore be used as a substitute for radium in conventional therapy, and it is enormously cheaper. Radium still costs about £5000 per gram and will always remain rather expensive because of the tedious extraction process from uranium ore, but the equivalent activity of cobalt-60 costs only about £20.

If a substance is concentrated in one particular organ of the body by normal metabolic processes and it is desired to irradiate that organ in order to destroy its tissue, then it is sometimes possible to incorporate in the substance a radioisotope which will also be concentrated in the organ and subject it to intense local beta irradiation. Phosphorus-32 and iodine-131 have been used therapeutically in this way. Phosphorus-32 has been used to control polycythaemia vera, where the blood contains too many red corpuscles, and it is also of value in controlling some other blood disorders. Iodine administered as iodide is readily concentrated in the thyroid gland and iodine-131 can be used therapeutically to destroy thyroid tissue in some cases of hyperthyroidism and a very limited proportion of cases of thyroid cancer. The therapeutic use of large doses of radio-active substances must still be regarded as experimental, and the results obtained so far have not justified early hopes.

Radioactive substances are used for diagnosis in medicine, and for biochemical investigation, by means of the tracer technique. If a compound is synthesised with some of its atoms radioactive, the radioactive compound will not differ chemically from the same stable compound, and wherever the compound goes in a chemical system or living body it can be detected by the radiations given off. Moreover if such a radioactive compound is decomposed, the radioactive element can be found in other compounds, and a series of reactions occurring in a living body may be studied. A compound synthesised with a radioactive isotope in a particular position in the molecule is said to be labelled with the isotope in that position. Any of the stable compound also present is referred to as carrier. The sensitivity of the tracer method is remarkable. If we consider a beta-emitting isotope of atomic weight about 40 and half life about 10 days, the weight of active material which can be detected and measured is as little as 10^{-15} grams.

The simplest type of tracer experiment is that in which the transport of a labelled element is being observed, irrespective of the compound in which it is combined. The first experiment in which this method was applied to a living system still remains one of the best examples of such a translocation study. Hevesy in 1923 studied the uptake and movement of lead in shoots of the horse bean, using as tracer thorium-B which is a naturally occurring radioactive isotope of lead. Solutions of different strength of lead nitrate were made up labelled with thorium-B nitrate and when bean shoots were placed in them the amounts of lead taken up and transported in the plant could be measured by the radioactivity appearing in the stem and leaves. It was found that in solutions containing little lead the roots were able to hold most of it from reaching the rest of the plant. When the plants were placed in solutions containing much more lead, however, a greater proportion got through to the stem and leaves.

Many such studies of gross metabolism of elements have now appeared. One is of great value in the diagnosis of disorders of the thyroid. Iodine-131 in the form of a very small amount of iodide is administered to the patient. Practically all that is not held in the thyroid is excreted in the urine. If a counter is placed over a patient's thyroid gland and radioiodide administered, then the γ-radiation from the gland will increase as more radioiodine appears there. If a curve is drawn of the uptake of iodine into the thyroid over a period of two or three days, it will be found possible to decide from it whether or not the patient's thyroid is functioning normally. The nature and to some extent the degree of dysfunction can be indicated by the shape of the uptake curve. External exploratory techniques of this kind are now in use, and several different disorders can be diagnosed by following the concentration or transport of a particular radioactive substance. The amounts of radioactivity administered to patients are only about 1 per cent of those which would be used in therapy and constitute a negligible radiation hazard.

By far the most fruitful field of tracer investigation has proved to be that of biochemistry, and particularly studies involving intact animals and living plants. The substitution of a radioactive ingredient for a stable one in the food of the living organism makes no difference to its growth or the fate, within the organism, of the substance in question. The amount of radioactivity in the compound examined must, of course, not be sufficient to cause radiation damage to the organism. It is generally possible in tracer researches to ensure that this important proviso holds.

The most important elements whose compounds are of biological interest are carbon, phosphorus, iodine, sulphur, hydrogen and nitrogen. As tracer isotopes, phosphorus-32, iodine-131 and sulphur-35 are generally used, while the stable nitrogen-15 is the only one suitable in the case of that element. Carbon may be traced with the use of stable carbon-13 or radioactive carbon-14, and most of the more recent work is with the latter. Hydrogen is usually traced with heavy hydrogen.

A radioactive element is administered in a known chemical form – often quite a simple one like carbon dioxide containing carbon-14, or a phosphate containing phosphorus-32. After a suitable time, compounds are extracted from plant or animal tissue and purified. If they are radioactive, then there must be normal processes by which carbon from carbon dioxide or phosphorus from phosphate are incorporated into those compounds.

It is possible to identify the compounds into which a radioactive element has been incorporated even if they are present in too minute amounts to be identified by normal chemical means. Suppose extraction has been carried out which yields a faint smear of a radioactive residue, too minute for chemical analysis. A guess is made as to its probable nature, a relatively large amount of the pure inactive substance which it is suspected to be is added, and the two are mixed thoroughly. Attempts are then made to purify the added substance from the radioactive residue. The specific activity of the mixture (activity per gram) is measured and the substance purified, say, by repeated recrystallisation. The specific activity of each successive crop of crystals will remain constant if the residue and the added known substance are chemically identical. Crystallisation to constant specific activity is therefore good evidence for the chemical identity of the residue. It is not quite conclusive evidence, because two chemical compounds might crystallise together even though they were not identical. The certainty of identification is therefore much increased if more than one method is used for the attempted separation of residue and pure substance. If two or three different kinds of purification methods all fail to separate the pure substance from the residue, there can be little doubt of the chemical identity of the two.

Tracer methods enable us therefore to find where a labelled element goes and to determine the compounds into which it is converted by chemical or biochemical processes. In some cases it is even possible to determine the order in which the labelled compounds form from one another.

One other method of using tracers which has very wide application is the so-called dilution technique. It is sometimes required to measure the total amount of a substance in a system from which it cannot be isolated and purified. An example is the estimation of one compound in a mixture with other very similar compounds. In this case either the separation of the required compound could be complete but it would be impure, or its purity could be high, but at the expense of losses during purification. This problem is susceptible to attack by the dilution method.

The substance which is to be estimated is made up with a radioactive label at an accurately known specific activity (concentration of radioactivity). A known amount of this labelled substance is introduced into the system containing the unlabelled substance and mixed with it. A sample taken from the mixture is then carefully purified and its specific activity measured. Thus a known amount of a substance at a known initial radioactivity concentration has been diluted with the unknown amount of non-radioactive substance in the mixture. However, the final radioactivity concentration has been measured, and therefore the diluting volume of stable substance can be calculated. It is no longer necessary to isolate the whole substance from the mixture, since any fraction of it contains the same ratio of stable to radioactive atoms.

Another example is the estimation of the total amount of a particular substance in a *living* animal. For instance, a medical application of dilution technique is found in measurement of blood volumes in human patients. A sample of the patient's blood is withdrawn. The blood is shaken with a little radioactive phosphate solution and washed in saline solution. These red cells incorporate some phosphorus-32 in a very firm chemical combination without being damaged. The specific activity of the labelled cells is then measured and a known amount re-injected into the patient. After allowing sufficient time for the labelled and unlabelled cells to mix thoroughly, a further sample of blood is withdrawn and its specific activity measured. The quantity of blood which has diluted the labelled cells can therefore be calculated, and this is the total quantity of blood circulating in the body of the patient.

Industrial Applications

There has been a definite time lag in the application of radioactive techniques to industrial problems. Publications in the biological field number many hundreds, while those in the industrial field number probably less than a hundred. This state of affairs is unlikely to last for very long, as considerable efforts are being made to exploit radioactive techniques in industrial research and practice. The type of tracer research which appears to have the widest potential industrial applications is that of following the transport of a substance, and in addition there are many instances in which the properties of radiation can be exploited in apparatus for special purposes. Some of the examples which will be discussed are British, some American, and others are so far merely speculative suggestions which may, however, lead to definite applications in the near future.

Let us first consider a company which is in the business of liquefying air and separating its components. In addition to recovering nitrogen and oxygen this company is interested in recovering the rare noble gases, such as krypton and xenon, for which demand has recently outstripped the available supply. There is only one-tenth of a part per million of krypton and a hundredth of a part per million of xenon in air. It was found that only a small proportion of the available krypton and xenon were being recovered and it was necessary to find out where these materials were concentrating in their process and how to make changes so that better recovery could be achieved.

Tracer techniques are admirably suited to this problem of tracing an infinitesimally small amount of an element dispersed in an enormous volume of a diluent such as air. Radioactive krypton and xenon, if introduced with the incoming air prior to liquefaction, will permit analysis at any point in the process even down to a few parts per billion. A Geiger counter for measuring the radioactivity content of the gas at various points in the process will indicate the amount of krypton or xenon present with an accuracy as good as 1 per cent. This is made possible by the fact that the radioactive krypton or xenon introduced with the incoming air remains in a fixed proportion to the non-radioactive krypton or xenon which is naturally present in air. By this means the fate of the rare gases can be established and the appropriate changes made in the process.

In the manufacture of engines, it is important to know how much a given bearing will wear under particular conditions of running. If the bearing is weighed, there is no detectable difference in weight between the beginning and end of a test of reasonable length, and if the wear debris from the lubricating oil is concentrated and weighed, this will only reveal the total amount of debris present in the engine, and will not determine the wear in any one particular bearing. If the bearing it is desired to study is made radioactive by irradiation in a pile, only the debris which comes from this bearing will be active, and a measurement of the activity in the oil will determine how much of the bearing has been worn away. If a cast iron bearing is used, it is readily possible to detect down to one-tenth of a milligram per litre of oil by immersing a photographic film in the oil, developing it after suitable exposure, and measuring with a densitometer the blackening which has taken place.

In laboratory studies on the effect of lubrication, it is often desired to measure the amount of metal transferred from one surface to another, when these amounts are microscopic, and even when the two metals are the same chemically. This is possible by irradiating one component so that it becomes active, while the second one is not. The amount of activity transferred to the inert component can readily be determined by radioautography.

In most tracer techniques which have been considered so far, the radioactive tracer has exactly the same chemical composition as the labelled substance. In many cases this chemical identity is not essential. For example, in the spinning industry, it is a matter of some importance to apply a uniform coating of oil to a fibre before it is woven. If the coating is uneven, weaving and dyeing will be badly carried out, and the results will be patchy. The amount of oil per centimetre of fibre is extremely small – about 10^{-10} grams – and ordinary methods of measurement can only determine

the average amount of oil over several metres of fibre. If a small quantity of an active compound such as ethylene dibromide, which has been irradiated in the pile, is added to the oil before the fibre is treated, this compound is applied to the fibre with the oil. Provided only that the compound chosen is miscible with the oil in the proportion used, and that the mixture is thoroughly stirred before treating the fibre, the activity throughout the oil will be uniform. If the treated fibre is then stretched on a drum covered with a photographic emulsion, a radioautograph is obtained which will show irregularities in the amount of oil applied over as little as two mm. of fibre. In common with many other tracer methods, this is suitable only for pilot plant operation, since the amount of activity which it would be necessary to use in large-scale operations would constitute too great a hazard to the health of the workers.

A problem of a different kind which has been solved by the application of isotopes is that of locating survey reference marks in open country. It is frequently necessary to run surveys over large areas, and often over land which is being farmed. Survey stakes are put into the ground at intervals of a few hundred feet. It is often necessary to bury these reference stakes a foot underground to prevent interference with ploughing and farming, and in other cases where the land is not cultivated they are overgrown with vegetation in the intervals between survey. When the stakes are required for use again, a new survey is required to locate the approximate spot where the stakes were placed, and an area several feet in diameter has to be dug to find them. Experiments have shown that if 10 microcuries of cobalt-60 are incorporated in the stake, for example in the form of a cobalt-plated nail driven into it, the cobalt can be detected with a portable Geiger counter survey instrument through a foot or more of earth. The cost of the radio-cobalt is negligible, and the portable Geiger equipment more than repays its cost in a day or two of working.

In the metals industries, isotope techniques will yield results which have been impossible to obtain with conventional methods, for example, by the addition of small quantities of radio tracer it is possible to determine the relative volatility of various components of alloys and to measure their vapour pressures. This technique is particularly useful when small quantities of a relatively volatile constituent are present in an alloy. It can be used for measuring the rate of volatilisation of zinc in the making of brass.

It is of considerable interest to know how surface coatings of metals diffuse into the inner layers of the parent mass as a result of heat treatment. A reasonable amount of work on this problem has already been done by the tracer method. For example, diffusion can easily be studied by depositing a thin layer of a radioactive metal such as iron-69, copper-64, cobalt-60 or nickel-59 on the parent mass by rolling or plating. After heating the metal block in an annealing furnace, successive layers of the surface metal are removed with a milling machine and each layer is dissolved and counted in an appropriate form of Geiger counter. This can be carried out on layers as thin as one ten-thousandth of an inch and the measurement of the specific activity of each layer enables a quantitative measurement of the extent of diffusion of the metal coating to be made.

It is frequently desired to know how the components of a given alloy are distributed. For example, this may shed light on how the impurities which prevent a metal from having the required physical properties exert their effect. If an investigation on the role of phosphorus is required, phosphorus-32 is introduced in small quantities into a melt of the particular alloy and an ingot is prepared in the normal way for metallographic examination. A fast X-ray film is then placed in contact with the surface and a radioautograph is produced. This will determine whether the phosphorus has segregated along the crystal boundaries in the metal or is taken into the crystal structure.

Tracer technique can be used in certain cases to detect small quantities of impurities in a substance, for example, a metal alloy, which are difficult or impossible to find by chemical means. Sulphur and selenium are particularly objectionable impurities in some metal alloys, and their detection by normal chemical analysis or spectrographic analysis is difficult because they are present in such traces. They can, however, be analysed by an activation technique. A known weight of the alloy concerned is irradiated in the pile for a known time, and then dissolved and a small amount of stable carrier sulphur and carrier selenium added. All the sulphur and all the selenium, radioactive as well as stable, are separated off by chemical means, and then examined with a Geiger counter to measure the final specific activity, which depends on the amount of sulphur and selenium initially irradiated. By this means ten parts per million of selenium and about fifty parts per million of sulphur can be measured without any difficulty. This technique is available for other analytical purposes, but in general should be only used where normal methods do not apply.

A range of instruments has been produced or suggested for the purpose of using radioactive materials as convenient control devices. In many industries which produce material in thin sheets, e.g. paper, leathercloth, sheet metal, rubber, it is necessary to control the thickness of the product within fine limits. So far, no satisfactory method of doing this without touching the surface of the product has been applied on a large scale. In the case of paper, an answer has been found by the use of radioactive calcium, calcium-45. This isotope has a half-life of 172 days and emits beta radiation of a maximum energy of 0.3 MeV. As the beta particles pass through matter they are gradually slowed down and stopped, and those with least energy are stopped first. If a thin piece of paper or other material is placed on top of the calcium source, the number of beta particles which pass through the paper will depend on the weight per unit area of the paper. The thicker the paper the fewer beta particles will pass through it. If a Geiger counter is placed on the opposite side of the paper from the source, the number of counts in a given time will depend only on the weight per unit area of the paper interposed between source and counter, and if the counter is connected to a counting rate meter, this can be calibrated in terms of thickness of paper, if it is all the same grade, or of weight per unit area if different grades are to be encountered (pl. 19).

For single measurements this arrangement is adequate, provided that the calibration is checked to allow for the decay of activity of the calcium source. If, however, it is decided to run a continuous control process, two parallel systems are required, one of which operates on the paper being produced by the manufacturing process concerned, and the other of which operates on a standard piece of paper to which the process is to be controlled. The outputs of the two counting rate meters are connected, so that when the two samples are identical, there is zero output from the final circuit. This final circuit may take the form of a meter mounted in front of the operator, where hand control is required, or may be a control voltage fed to a servo mechanism where automatic control is required. The range of usefulness of the calcium-45 source for this purpose is for paper thicknesses from 0.003 to 0.025 of an inch roughly, but suitable sources are available for thicknesses smaller or greater than this, up to about one-tenth of a gram per square centimetre. Where weights per unit area in excess of this are to be measured, the same principle is used with a source emitting soft X-rays or gamma rays. These are absorbed exponentially in the material, and a suitable source is available for almost any requirement. The sources used in all these applications are of such low total activity that no special precautions to avoid health hazards are necessary in their use.

Another instrumental application is in the control of the level of the liquid inside a sealed tank. A small amount of gamma-emitting material is placed on a float which can move only in a vertical direction by sliding along a pair of

rods. A Geiger counter is mounted on the outside of the tank at the top in a convenient position and is connected to a counting ratemeter. The output of the counting ratemeter is connected to a control tap and more liquid is allowed to enter when the float falls below the required position and the number of counts per unit time drops below a pre-set datum.

Another problem for which radioactive material has been used is the question of determining when the grade of oil which is being pumped along a pipe changes abruptly. In a long pipeline, the change of grade made at the sending end will reach the receiving end after a time which may vary somewhat, and unless a tedious sampling technique is used, it is difficult to determine exactly when the change-over at the receiving end should be effected. By injecting a small quantity of active material as the first of the new grade oil is pumped in, the front of this grade is effectively labelled so that a counting meter outside the pipe at the receiving end will indicate clearly by a sudden change from a low to a high counting rate when the front of the new grade oil arrives.

A field in which radium and its daughter product radon have been used for some time is industrial radiography (X-ray photography). In many problems of radiography encountered in industrial practice, it is essential to have the source of radiation small and readily transportable. For example, in producing radiographs of the sternpost of a ship, it is impossible to install an X-ray generator of the electronic type inside the ship at the appropriate point, but a gamma ray source which is only a few cubic mm. in size can be placed wherever required without difficulty. In addition the radiation is emitted in all directions, so that, for the examination of metal castings, a large number of castings can be placed in a circle with the source at the centre and a large number of radiographs can be taken at once. This means a considerable economy in the working time of the radiographer. Radium as a tool in industrial radiography is likely to suffer competition from cobalt-60, just as it is in the medical field, and the artificially produced material will almost certainly supplant the more expensive product. Cobalt-60 has a half-life of 5.3 years and can be prepared with the same specific activity as radium. The gamma rays of radium and cobalt-60 are all of energies about 1.2 million electron volts and are most useful where photographs are being taken of castings several inches thick. For making radiographs of smaller and thinner metal objects, less energetic gamma rays give much better contrast. Several suitable artificially produced isotopes are now being produced for such purposes, and these will cover a field in which work was previously done with expensive and bulky X-ray generators.

A final most important application of radioactive isotopes lies in the dissipation of unwanted static electricity. In a number of industrial problems, moving belts of insulating material pick up large quantities of static by passing over metal or insulating rollers. If no attempt is made to dissipate this static harmlessly, it may build up to the point where sparks shoot from the belt to the nearest earth point, and if inflammable vapours or liquids are present, as in the plastics industry, it may constitute a serious fire hazard. Even if the sparking point is not reached, the product is rendered extremely difficult to handle and a considerable amount of wasted time and raw material results.

The static conditions vary with the weather, because of the variations of humidity in the atmosphere. Because of this, some factories have attempted to make the air sufficiently conducting to dissipate the unwanted static by raising the humidity and the temperature to levels normally encountered only in climates such as Aden and Singapore. Although this may dissipate the static, it has an adverse effect on the machine operators and causes a considerable turnover of labour.

Other methods adopted to dissipate static have consisted of attempts to make the air conducting by high voltage brush discharges or by irradiation with ultra-violet light.

In some cases, a conducting path has been established by means of what is known as a 'wet lick', for example, a damp fibre or belt rubbing against a moving material and connected to a good earth so that a physical path is provided to conduct away unwanted static. These methods all have their drawbacks: electrical installations are costly and require considerable servicing, and the 'wet lick' method is liable to damage the moving belt by friction.

By the choice of a suitable source of radiation, however, it is possible to ionize the air over a fair volume surrounding the moving belt so that the ionization current between the belt and earth conducts the charge harmlessly away. Alpha emitters have occasionally been used for this purpose, especially in America, but they have the drawbacks that the ionization is produced only in the immediate vicinity of the source and that alpha-active material is difficult to prepare in suitable form. Beta emitters such as thallium-204 or strontium-90 appear to be more suitable, since ionization occurs over a region extending two or three feet from the source and they do not suffer from the mounting difficulties associated with alpha emitters. As these materials become more readily available, many static problems may be solved in existing plant and provision made to guard against static in plants which are at the design stage.

Before embarking on radioactive techniques in industrial work, a few points should be considered. Firstly, it should be clear that the problem is one in which radioactive methods have a real advantage over existing methods. Secondly, it is necessary to make sure that research workers are adequately trained in handling radioactive materials, and finally, that it is possible to dispose safely of any radioactive waste products if these are present in quantity sufficient to constitute a health hazard. If these considerations are kept in mind, it will be found possible in very many cases to make use of isotope techniques with considerable success.

The Atomic Energy Research Establishment at Harwell conducts an advisory service which will provide any degree of assistance required by potential users of isotopes. The assistance given ranges from preliminary discussions to the design and carrying through of complete experiments, and this service is continually expanding.

8

A Note on Health Hazards

J. L. CRAMMER

RADIUM and X-rays were both discovered just over half a century ago; and it was not long before it was noticed that both had a powerful effect on living things. The radiation from radium includes γ-rays, the biologically most important part of the radiation, which have been shown to be physically identical with high-energy X-rays. So it is not surprising that the medical effects of radium and X-rays are in general alike, whether it is a case of over-exposure resulting in radiation sickness, or of controlled irradiation for the treatment of cancer. Deep X-ray therapy and radium both kill the cells of a malignant growth, and the choice between them depends primarily on the position of the tumour in the body.

The early workers with X-rays suffered mutilation and even death before it was realised that screening was essential to shield them from the daily exposure to the radiation. Since then, in spite of the introduction of ever more powerful X-ray generators, and the spread of the use of X-rays for diagnosis and treatment to almost every hospital, the work of the radiographer and the radiologist has become reasonably safe. The industrial use of radium likewise had its dangers, at first unsuspected. During the war of 1914–8, instrument dials were painted with a paint containing radium, so that the figures would glow in the dark. In the early twenties, a number of the workers involved began to get cancer of the bones: it appeared that they had been in the habit of frequently licking their brushes, and on each occasion had absorbed a little of the radium paint. Over the years the radium had accumulated in their bones, and its continued emission of radiation had upset the neighbouring tissues and caused them to break out in the revolt from the body's control which is cancer. Later still, it was noticed that the miners who worked in the uranium mines of Joachimstal in Czechoslovakia were unusually liable to cancer of the lungs, which apparently developed when there was many years' exposure to an atmosphere containing the radioactive gas radon, given off in the long course of the decay of uranium, through radium, to lead. The fact that miners in Canada (see plate 18) have no increased liability to cancer is attributed to the great precautions taken, including a much shorter exposure to the radiation.

In the twenties and thirties of this century, a considerable amount of human experience was thus collected, supported by a great deal of experimentation on rats and rabbits, the fruit fly *Drosophila*, and many other animals and plants, and it was clear that the effects of radiation depended on the dosage given, and the amount of body exposed. A single very large whole-body dose could kill; a smaller single dose could produce the illness, radiation sickness; a long series of smallish doses might result in cancer; and a single medium small dose would interfere with the division of cells or might produce mutations, changes in the genetic material of the cell leading to inheritable new characteristics.

Some precise values for these doses are given a little later on, but it is important to realise that they assume that the whole body is receiving the radiation. Some internal organs are more sensitive than others: while 500 roentgens applied to a man's whole body may kill him, twice this dose limited to the skin of his forearm merely produces a little redness, while a tenth of the dose on his bone marrow is enough to stop its white cell output into the blood for the time being.

Dividing cells, in fact, are the most sensitive to radiation; the bone marrow which makes the white cells of the blood, and the reproductive tissues in the ovary and testis which produce ova and spermatozoa, are amongst the more sensitive of the body's organs. But though dosage is important it cannot be the only factor at work, because different species of animals have different sensitivities: it requires more radiation per cubic centimetre to its whole body to kill a mouse than a guinea pig, and more still to kill a rabbit. Even different individuals have different sensitivities, and what will injure one rabbit will leave another unharmed, so that research has to be carried out on large groups and the results expressed statistically.

All the three kinds of radiation – α-particles, β-particles, γ-rays – produce their effects by ionization. That is to say, as they pass through atoms in their track, they may tear off one of the electrons circling round the nucleus of each atom. An atom without its full complement of electrons is electrically unbalanced, charged, an ion; and if it forms a molecule with other atoms, this molecule may now be disrupted by the unexpected ionization and the resulting unbalance of electrical forces. Sometimes the molecular fragments are highly reactive, and proceed to attack other molecules in a purely chemical manner, so that a long sequence of chemical (and therefore physiological) changes can be started, in the short time before the ion originally formed picks up a spare electron and becomes a neutral atom again. Neutrons produced in atomic piles and bombs (they do not occur naturally, of course) do damage in much the same way, by ionization. Fast neutrons collide with atoms and recoil leaving fragments in their wake; thus hydrogen atoms become hydrogen ions (protons). Slow neutrons are captured outright by atomic nuclei, chiefly those of hydrogen (with liberation of γ-rays) and of nitrogen (which subsequently ejects a proton). In living tissues, this ionization acts in two ways, splitting the genes and chromosomes and cell proteins directly, and also splitting some of the water, which every cell contains, into the highly reactive H and OH radicles, which in turn inactivate various enzymes and upset the cell's functioning.

Because radiation produces its effects by ionization, its strength or dosage is measured in terms of a unit, the Roentgen or r, which is defined as that amount of radiation which will produce enough ionization in 1 c.c. of air (at standard temperature and pressure) to amount to one electrostatic unit of electric charge, either positive or negative. Since a single electron carries a charge of 4.77×10^{-10} electrostatic units, 1r means the production by ionization of approximately 2×10^9 electrons in every exposed cubic centimetre of air. In a volume of air about the size of an average living cell, say a cube with a thousandth of a centimetre side, this means about two ionizations. Since density of ionization is roughly proportional to physical density and cell protoplasm is about one thousand times denser than air, this means that the living cell itself would contain about 2000 ionizations when exposed to radiation of 1r.*

What does this dosage unit, the roentgen, mean in biological terms? 500r is enough to kill half the mice exposed to it; 1r per day for two years (a total of 730r) produced no observable effect on rats, dogs, rabbits or monkeys; eight human patients suffering from cancer were given a total of 300r in eight days without noticeable ill-effect – but it is probable that 500r might have produced sickness, and very probable indeed that 1000r would have been lethal for most of them. Clearly it is impossible to find out experimentally what the radiation dose is which will kill 50 per cent of the people exposed to it, so there is bound to be a certain amount

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*Note that the roentgen is, however, a macroscopic unit, and does not really say very much about what is going on microscopically inside single cells. A tissue exposed to 1r of X-rays will have random ionisations, 2000 of them on the average in each cell of the tissue; but 1r of particles, especially protons (hydrogen nuclei) and α particles (helium nuclei) means ionisation produced very heavily in the actual track of each particle but not elsewhere, so that the damage done is not thinly spread out over a wide area and therefore weak, but concentrated in a few localities and therefore great. In other words, the 'biological efficiency' of a radiation depends on its composition as well as its dosage.

of speculation as to the most likely value. On the other hand, what has been long proved to be a harmlessly small dose is much better known, and 0.5r per week is taken as a harmless human exposure to γ-rays. This 'tolerance dose' is what a man can receive to every cubic centimetre of his body at once without ill-effect.

From the doctor's point of view, the effects of overdosage must be watched for, and one of the first signs is found in the blood. The normal bone marrow is very active, its cells continually dividing and multiplying to give rise to all the red cells and most of the white cells of the circulating blood, for these circulating cells are continually dying and needing replacement. Such a system is particularly radiosensitive, and it is not surprising that an early effect of over-irradiation should be an arrest of the bone marrow's activity. First the number of white cells in the bloodstream falls rapidly, then the red cell count more slowly – a progressive anaemia; production of both kinds of cell is stopped at the same time, but white cells have a much shorter natural circulating life and are the first therefore to feel the lack of replacement. This change in cell-counts in the blood is a very valuable thing, but it requires expert interpretation, because so many other diseases can produce not dissimilar pictures. The illness, glandular fever, appears now and then as one such trap for the unwary.

Full-blown symptoms of radiation sickness were most studied after the explosions at Hiroshima and Nagasaki. Those who survived but had been close enough to receive a large dose of rays with the flash from the bomb either died suddenly in about 48 hours, or after a little feeling of sickness and perhaps vomiting once or twice on the day of the explosion, were apparently perfectly fit for one or even two weeks after (depending on the size of their radiation dose), and then began to get fever, and diarrhoea, and to feel extremely weak, and their hair to fall out. At the same time, examination of the blood showed lack of white cells and a progressive anaemia, and they were subject to frequent haemorrhages, perhaps due to a failure of the clotting mechanism of the blood. The white cells normally play a prominent part in defending the body against infection: patients with few white cells are very liable to pick up some germ, and die from it. If a patient can be kept going with blood transfusions and with anti-bacterial substances such as penicillin, however, there is quite a good chance that the bone marrow may suddenly recover and become active again, and then all is well. If this does not happen, death is certain. (It may at this point be worth re-reading pages 117–120, 'The Physics of the Bomb' to appreciate the irradiation risk at Hiroshima and Nagasaki.)

Radiation sickness of this degree is of course very unlikely to occur in peace-time because the atomic piles are situated away from centres of population, and are very carefully controlled and shielded. In any case a pile is not a bomb and is incapable of blowing up like one: if the neutron level did rise too high the whole thing would melt and flow apart rather quickly, thus automatically damping itself down and preventing a true explosion. The danger that does exist is of chronic illness induced by small daily overdoses in those working around the piles or with radioactive materials, and apart from the presence of neutrons it is a danger about which a good deal was known prior to 1939, and enormous precautions are taken against it. The difference the neutrons make is a difference in the shielding required, and in the instruments to give warning of their presence.

A shield to stop γ-rays is efficient in proportion to its density: thus a concrete screen has to be about four times thicker than a lead one to give the same efficiency of block, while steel is intermediate. On the other hand fast neutrons must first be slowed by collision with a light atom such as hydrogen or carbon, and then when they are moving at 'thermal' speeds they will be captured by the atoms of the screen. Each thickness of a foot of concrete reduces both gamma rays and neutrons to one-tenth of their previous value, and a reactor generating 10,000 kilowatts will need eight or nine feet thickness of concrete round it, so that the total weight of the whole thing will be at least 100 tons. (It is for this reason of weight that atom-powered motor cars are so unlikely: but a 200-ton aeroplane is not out of the question, as the Brabazon is on the way to this with its 140 tons.) In addition to shielding, every effort is made to permit of remote control operations (see, for instance, plates 9 and 10).

In addition to shielding, there is monitoring. Instruments are everywhere to register the rays and neutrons. Workers wear a film badge – a piece of X-ray photographic film partly encased in lead – which blackens as it receives radiation, and so developed after a fixed time, for instance a week, records the total γ-radiation its wearer has received. A pocket electroscope worn like a fountain pen does the same thing. It is charged at the beginning of the day, and the charge leaks away whenever ionizing radiation reaches it: hence a reading of the electroscope at any time gives a measure of total γ-radiation received up to that moment. Larger, but portable instruments are the ionisation chambers and condensers where the formation of ions by radiation permits a flow of current or a partial discharge of a condenser. The ionization chamber measures the dose rate – the amount of radiation arriving per second; so does the Geiger counter. Fast neutrons are detected by filling the ionization chamber with hydrogen: the neutrons strike the hydrogen nuclei and produce fast protons, with of course a positive charge. Slow neutrons strike boron trifluoride gas and break up some of its atoms with the production of alpha particles – and ionization. Not merely is a watch kept with these instruments on the 'hotness' of work benches, and experimental areas, but the monitors scan everyone passing through certain doors, and at the end of the day a special foot and hand check is held in case radioactive material has been caught on boots or under fingernails (pl. 12).

All this has become a speciality on its own called 'Health Physics', and with the provision of a routine medical service, gives very adequate safeguard. But the whole of this discussion has been written on the assumption that all radiation risks come from outside the body; so that alpha particles are negligible, since they are unlikely to penetrate the skin; and beta particles of equal unimportance since though they penetrate further into flesh, they are stopped by clothing; though a bare hand placed for a few seconds in the beam of a cyclotron will receive a burn which takes months to heal. If, however, people are unlucky enough to get radioactive material inside them, by accidentally swallowing some, for example, the situation is rather different, since shielding in the ordinary sense is quite impossible. Analyses of the breath, urine, etc., with the help of ionisation chambers can show the presence of radioactivity and the magnitude of the clinical problem. Treatment must be devoted to provoking the rapid excretion of the 'hot' material, since this is the only way of preventing irradiation internally and indiscriminately by all types of ray. For a number of substances such methods of treatment are being tried out, but each material has to be handled on its merits.

In a note of this brevity it would be impossible, even if security considerations permitted it, to discuss the question of defence against radiological warfare. Likewise the possibility that radiation overdosage may produce, in addition to or instead of radiation sickness, cancer at a later date, or inheritable defects in subsequent children, has not been raised: it is at present a speculative risk, without direct evidence of actual cases to support it. The radio-isotopes supplied for scientific work up and down the country are usually of too low a strength to constitute a health hazard, unless handled with gross carelessness, and the dangers discussed have chief relevance for workers with nuclear reactors, cyclotrons, and similar plant.

For those who need to go seriously into this subject *The Science and Engineering of Nuclear Power*, Volume II, Chapter 16 (Addison-Wesley Press, U.S.A.), is the best basic

account, while *The Action of Radiations on Living Cells*, by D. E. Lea (Cambridge University Press, 1947) is a standard textbook on the academic side. The current literature is best entered by looking through such scientific journals as *Occupational Medicine*, *Radiology*, and *British Journal of Radiology*.

9

The Tools of Nuclear Physics

O. R. FRISCH, O.B.E., F.R.S.

THE recent spectacular success in unlocking the large amounts of energy contained in heavy atomic nuclei was made possible through a long and patient process of investigation and interpretation through which physicists gradually gained some insight into the structure of that small core of very dense matter which is at the centre of every chemical atom and comprises nearly all its weight. Becquerel's chance discovery of what came to be called radioactive phenomena started a series of dramatic investigations through which some of our firmest scientific beliefs, such as the immutability of elements and the conservation of both mass and energy, came to be replaced by wider concepts, and which laid the foundation for our present knowledge of the structure of atoms. It was soon discovered that radioactive bodies liberated, at a very low rate, very large amounts of energy; but for a long time all attempts to control the release of these energies were utterly unsuccessful. The amounts of energy which were released by 'atom splitters', although tremendous in proportion to the minute amounts of matter involved, were ridiculously small compared with human needs. Yet the effort of the atom splitters was not wasted, for through their labours the knowledge was accumulated which eventually permitted us to solve the problem of controlled release of nuclear energies.

Nuclear physics is usually understood to mean that field of knowledge and endeavour which concerns the transformations of atomic nuclei. The electric charge, the mass, the magnetic moment, the size and the shape of atomic nuclei have been explored by means which do not involve

their transformation; these investigations are not usually regarded as part of nuclear physics.

Until around 1930 nuclear physics was essentially the study of radioactivity. The task of the physicist was to observe what happened; he did not have to produce the phenomena he wanted to study. He had to isolate, out of a number of things happening all at once, the one to which he wanted to pay special attention, and he had to set up instruments which were sufficiently sensitive to the phenomenon in question.

In later years we have learnt to produce nuclear transformations artificially, and now the observation of radioactive substances forms only a small part of the activities of nuclear physicists. Large and spectacular machines (of which the cyclotron is only one much publicised example) were built for the 'smashing of atoms', and large and spectacular advances in our knowledge have accrued from their use. At the same time, the tools for observing nuclear transformation are still basically the same as before 1930, although their scope, speed and accuracy is constantly being increased.

I shall therefore begin my report on the tools of nuclear physics with a description of the 'detecting tools' used to observe the phenomena which accompany nuclear transformations (spontaneous or artificial). This will be followed by a chapter on the 'attacking tools' used to produce nuclear transformations; their description will be necessarily incomplete, owing to the great complexity of these machines. Finally I shall discuss the way in which these two kinds of tools are employed together, and some of the techniques which are needed in order to isolate one particular phenomenon for study.

DETECTING TOOLS

All nuclear transformations result (directly or indirectly) in the appearance of fast-moving, electrically charged particles. On their way through air (or some other gas) these particles collide with molecules on their path, frequently tearing off an electron in the process; this electron usually attaches itself to some nearby molecule. As a result, the particle leaves a trail consisting of molecules some of which have lost an electron and are thus positively charged while others have gained an additional electron and therefore carry a negative charge. Such electrically charged molecules (or atoms) are called ions, and the process by which they originate ionization.

The ionization of gases by fast-moving electrically charged particles forms the basis of nearly all existing methods for the observation of nuclear transformations.

The Cloud Chamber

C. T. R. Wilson (Cambridge) invented a method of making the trail of ions visible. The method consists in attaching a droplet of water to each ion, by condensing moisture out of the surrounding air. When air is compressed it becomes hotter (as your bicycle pump will tell you); when it is expanded it becomes colder. Water, if left in contact with a limited volume of air, will evaporate only until the air is saturated with water vapour; the amount of moisture needed to saturate the air is greater at higher temperature. If moist, saturated air is suddenly expanded it comes to contain more moisture than its lowered temperature warrants; it is supersaturated. The excess moisture condenses on whatever is at hand and if the supersaturation is strong enough individual ions can act as nuclei for condensation. Each ion then becomes a small droplet of water, and the trail of ions looks like a fine streak of cloud not unlike the white trails which are sometimes produced by high-flying aircraft. To summarise, the method consists in letting the particles under investigation pass through moist air which is then suddenly expanded.

The instrument designed to put this method into effect is called a cloud chamber or expansion chamber. Numerous types have been built to suit special requirements. A fairly typical chamber is shown diagrammatically in Fig. 18. The top is a glass plate, the sides are formed by a glass ring. The bottom of the observation volume is a perforated metal sheet covered with black velvet, which acts as a background against which the cloud tracks can stand out clearly. Below this there is a rubber membrane which separates the expansion volume from the auxiliary volume. The latter is at first filled with air at a suitable pressure (adjusted with the help of a manometer), pushing the rubber membrane up, as indicated in the diagram. When the expansion is wanted the conical valve is opened; air rushes from the auxiliary volume into a large, previously evacuated, container, sucking the rubber membrane against the bottom plate. In this way the air in the observation volume is suddenly expanded by a definite amount. The perforated sheet and the velvet

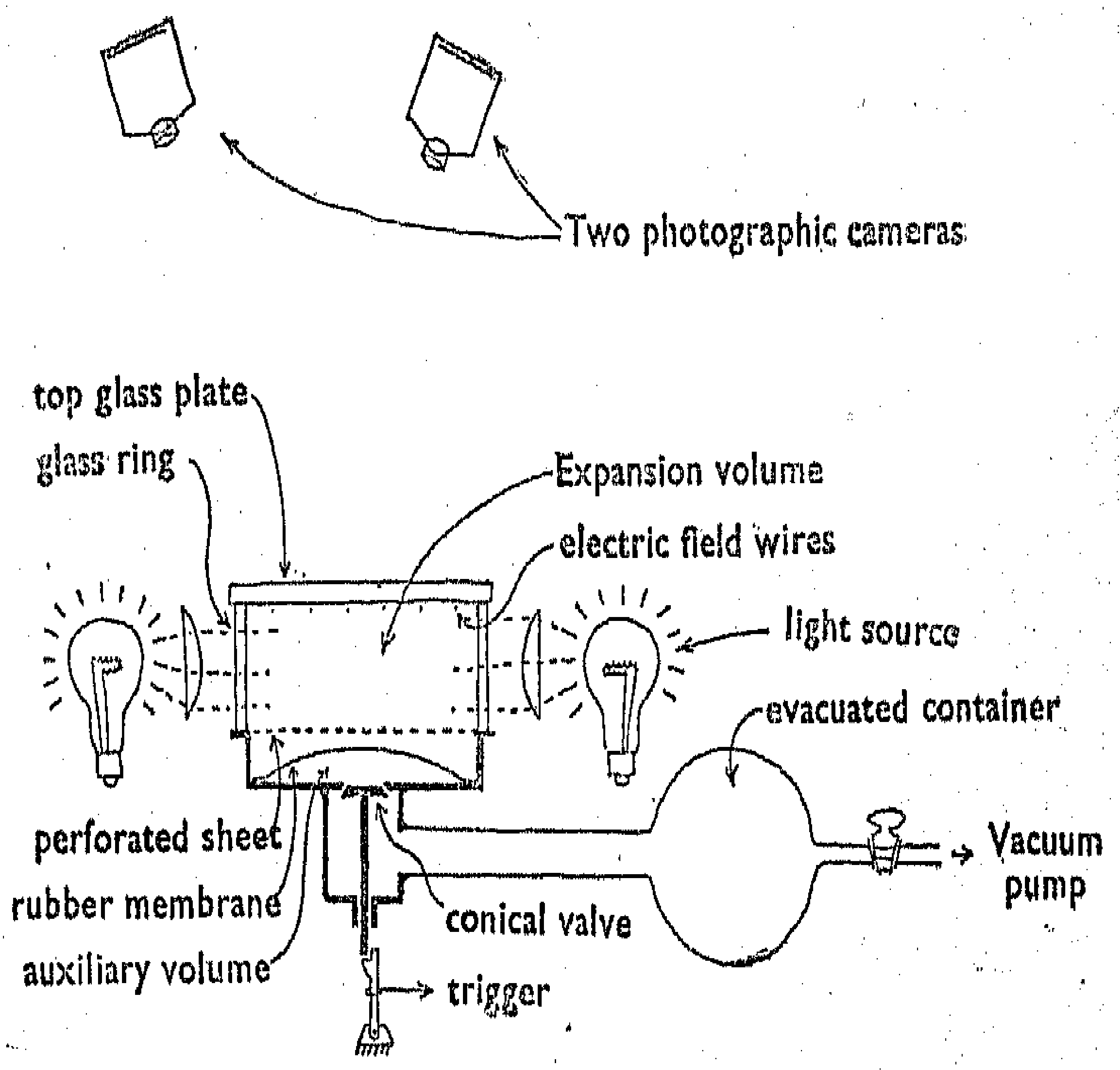

Fig. 18. Cloud chamber, schematical.

prevent any eddies, created by the sudden motion of the rubber membrane, from disturbing the droplets in the observation volume. Before assembling the chamber, the velvet is made wet to provide a source of moisture.

Unless fixed by the formation of droplets, the ions take part in the thermal agitation of the gas molecules and drift apart rapidly; within a tenth of a second the trail has become so diffuse that it would give only a blurred wisp of fog if an expansion were made. In order to clear the cloud chamber of these old ions one has to have an electric field. Several fine wires near the top plate, kept at 100 volts above the potential of the perforated metal plate, will sweep out all ions as fast as they are produced, within a fraction of a second; the electric field can be switched off automatically, at the instant of the expansion.

The track of droplets remains visible and undistorted only for a second or less since the droplets quickly fall to the bottom. It is usual to take a photograph of the tracks within a fraction of a second after the expansion. Ordinary filament bulbs are frequently used as a light source; they give a very intense flash of light if momentarily run at about twice their rated voltage, and will yet survive a large number of flashes. Frequently two pictures are taken simultaneously from two different directions, so as to get a stereoscopic effect; from the two pictures it is possible to reconstruct the location of the tracks in the chamber completely, in all three dimensions.

Some typical cloud chamber pictures are shown on plates 13 and 14. In plate 14 alpha particles were obtained by putting a strong sample of thorium deposit inside the chamber; as a result a large number of alpha tracks was formed during a single expansion. The deposit emits alpha particles of two different speeds and hence the tracks are seen to fall into two groups, each of which consists of tracks having very nearly the same length. Alpha particles have a well defined range which depends on their velocity. As the particle travels through the air it loses speed until it is no longer

able to ionize air molecules, and its track comes to an end. Measurement of the range is a convenient way to determine the speed, and hence the energy, of the particle.

Electrons (see plate 13) give tracks which are far less dense and straight, because they produce far fewer ions over the same path length, and because they are more easily deflected by collisions. Their range is ill defined and usually much greater than that of alpha particles. The best method for measuring their energy is to place copper coils round the chamber and send an electric current through the coils, creating a magnetic field in the chamber. In such a field, electrons are deflected so that they run in a curved rather than in a straight line. There is a simple relation between the amount of curvature, the magnetic field intensity, and the energy of the electron, from which the energy can be calculated.

The cloud chamber can also detect gamma rays and neutrons although they carry no electric charge and hence form no track themselves. Gamma rays are hard X-rays and consist of light quanta; they can impart enough energy to an electron for it to make a track in a cloud chamber. Neutrons do not interact measurably with electrons, but they do with nuclei. In colliding, for instance, with a hydrogen nucleus (a proton) the neutron rebounds, giving part of its energy to the proton. Hence a cloud chamber containing hydrogen will detect fast neutrons, through the tracks of protons which start inside the chamber for no 'visible' reason. Protons give straight tracks with a well-defined range like alpha particles, only somewhat thinner.

The visual and detailed character and the wonderful directness of the information which a cloud chamber supplies are advantages too obvious to need elaboration. Much of our confidence in the truth of our detailed descriptions of nuclear processes derives from the documentary evidence obtained from cloud chamber pictures. The drawbacks are better explained later, by comparison with other research tools.

The Electroscope

The electroscope is the oldest research tool of the nuclear physicist, indeed the oldest electrical measuring instrument. It gives only the most primitive sort of information and is not very sensitive, but it is simple, reliable, and accurate. In a typical design, the main part is a strip of very thin gold foil, hanging along one side of a vertical metal rod which is mounted on a good electric insulator (usually a piece of sulphur) inside a metal can (see Fig. 19). An electric charge is given to the rod by touching it momentarily with a charged wire (not shown in the diagram); the gold foil will then rise because of the mutual repulsion of the equal charges on it and on the rod. If there is no source of ionization present the rod will remain charged for a long time (many hours). If however the air in the can becomes ionized it becomes slightly conducting. Assuming, for instance, that the rod is positively charged, the negative ions will move towards it while the positive ions go to the wall of the can. As a result the rod gets gradually discharged and the gold foil slowly moves back to its natural vertical position. This movement can be observed by a low-power microscope mounted on the can, and the speed of the movement (measured with the help of a stop watch) is an indication of the intensity of ionization.

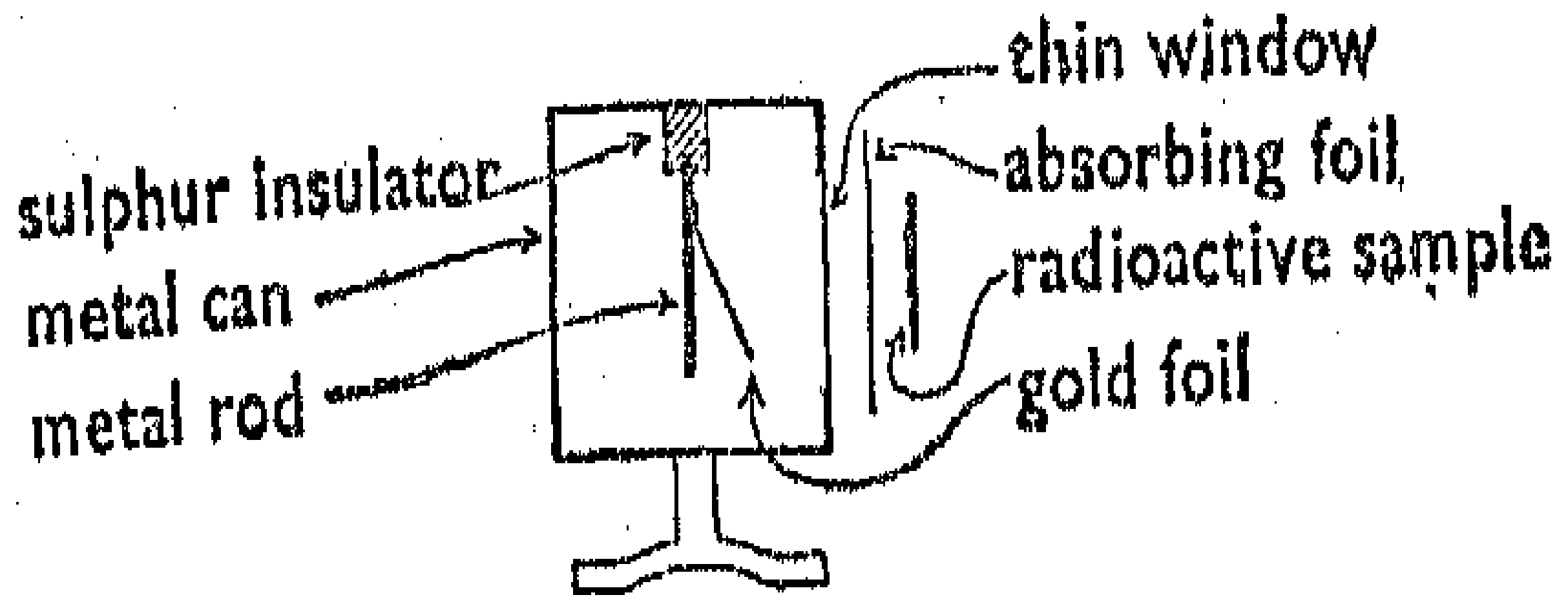

Fig. 19. *Electroscope, schematical.*

In contrast to the cloud chamber, the electroscope tells nothing about the nature of the particles which cause the ionization. On the other hand it is quantitative, it tells accurately at what rate ions are being produced. By varying the conditions it is even possible to analyse the radiation in a rough way. For instance, if the can has a window of very thin aluminium foil and an active sample is placed in front of that window, alpha, beta and gamma rays are able to enter the can. Interposing a sheet of paper will stop the alpha particles, and the corresponding decrease in ionization – as measured by the slower motion of the gold foil – indicates which fraction of the ionization was due to the alpha particles. A $\frac{1}{16}$ inch sheet of brass will stop all the beta rays (the electrons) and the residual weak ionization will be due to the gamma rays only. If one increases the thickness of the interposed absorber in small and accurately known steps and plots the observed ionization as a function of the absorber thickness one gets what is called the absorption curve of the radiations emitted from the sample. From this curve the composition of the radiation can be obtained in fair detail, and many properties of radioactive bodies have been determined in this fashion.

One drawback of the electroscope is its limited sensitivity. About a hundred alpha particles – or an even larger number of electrons – have to pass through the can to produce a visible shift of the gold foil. Numerous attempts have been made to improve the sensitivity of the electroscope, and among the rather complicated instruments (called electrometers) which were developed there are some which are so sensitive that the ionization due to a single alpha particle is not merely detectable but indeed accurately measurable. However these instruments are so delicate and so awkward to use that very little research has been done with them.

The Proportional Amplifier

Efficient detection of the ionization due to individual particles became possible only through the development of the radio valve. A considerable effort was needed at first to develop amplifiers which would magnify the tiny input signals (.001 volt or less) to an output signal sufficiently large to be recorded and yet accurately proportional to the amount of ionization.

Greinacher in Switzerland, Ortner and Stetter in Austria and Wynn-Williams in England were the pioneers of this development.

At the input end of the amplifier is the ionization chamber which the particles have to enter in order to be recorded. Some typical ionization chambers are shown in Fig. 20. The principal parts are the collecting electrode – a plate or rod of metal which is connected to the input of the amplifier – and the high-voltage electrode which is connected to a battery of a few hundred to a few thousand volts and which serves to create an electric field in the neighbourhood of the collecting electrode. The ions are set in motion by this field, the positive ions being driven towards the negative electrode and vice versa.

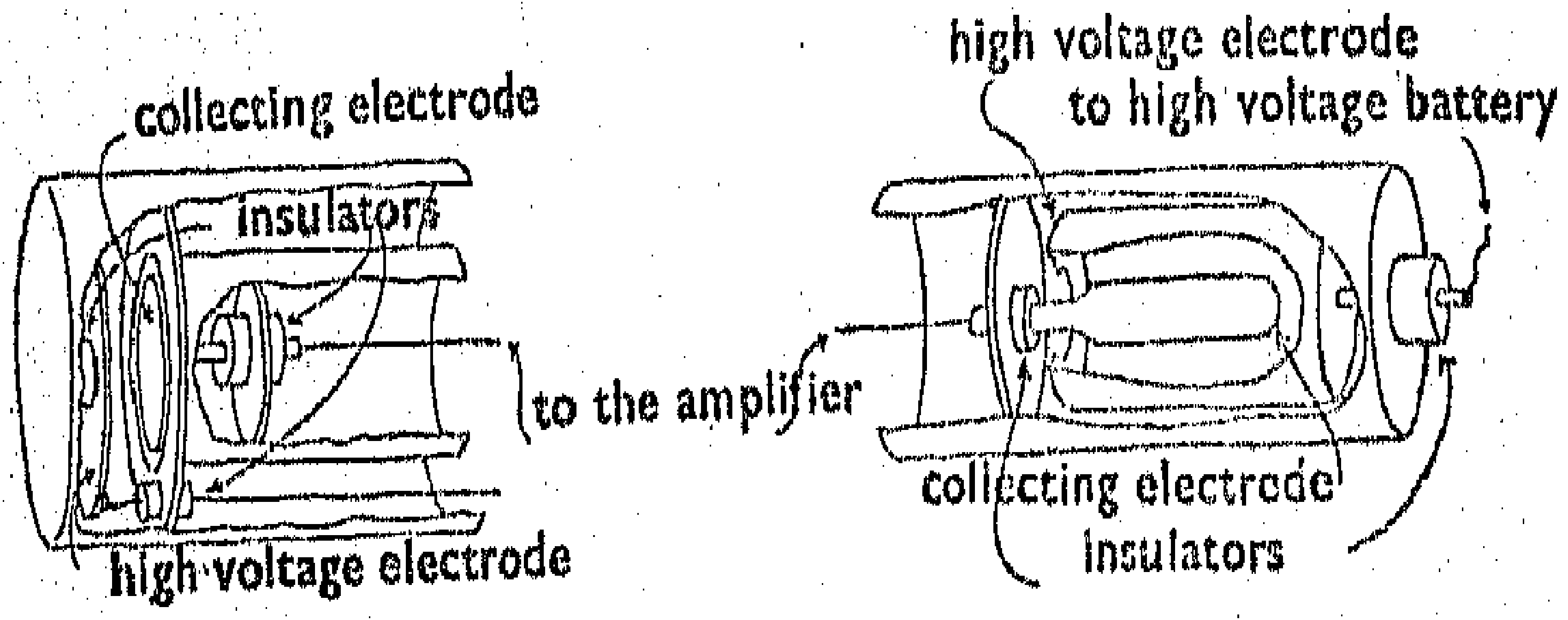

Fig. 20. Ionization chambers, section view.

Whenever an alpha particle runs through the chamber, leaving a trail of ions, a small current, representing the motion of the ions, begins to flow and continues (for a small fraction of a second) until all the ions have reached the electrodes. This brief current pulse charges the collecting electrode – and hence the input grid of the amplifier – to a potential slightly different from its normal value. This little potential jump is the signal which is magnified by the amplifier in the same way in which a radio amplifier magnifies the small signals picked up by the aerial.

There is a variety of recording devices which can be attached to the output end of the amplifier. The simplest and most common is a counting device such as is used in telephone exchanges to indicate the number of calls made by a customer during an accounting period. The device is set so that only pulses above a certain size will affect it; repeated counts with different settings give information on the distribution of pulse sizes, from which conclusions can be drawn as to the number and character of the particles passing through the chamber.

If one connects a loudspeaker to the output of the amplifier the individual particles become audible as sharp cracks above a persistent hissing noise. This noise is largely due to the random motion of the electrons in the first valve of the amplifier; by careful design it can be reduced but not entirely eliminated. It represents the limit to the size of signal that can still be detected; if a signal is so small that it disappears in the noise no amount of amplification will make it detectable. A particle has to create several hundred ions in order to produce a detectable signal; this is more than a fast electron will produce on passing through an ionization chamber of reasonable size. If one wants to detect individual electrons one must strengthen the signal before it enters the amplifier. This can in fact be done.

Gas Multiplication

If the electric field in an ionization chamber is made strong enough the ions will move so fast that they themselves become capable of ionizing the gas. The newly created ions join the race and in turn produce further ions. Thus we get a growing avalanche of ions (somewhat similar to the avalanche of neutrons in an atomic bomb), and the number of ions originally produced becomes multiplied through their interaction with the gas.

To make use of this effect it is common to use a thin wire for the collecting electrode; close to the wire the electric field is very intense and with a modest voltage of about a thousand volts on the other (cylindrical) electrode one can make it so strong that gas multiplication sets in. An ionization chamber designed in this fashion is frequently called a counter (see Fig. 21). By carefully adjusting the voltage one can obtain multiplication by factors up to a thousand and still get pulses which are approximately proportional to the original amount of ionization; used in this way the instrument is called a proportional counter. With increasing voltage the multiplication goes up very rapidly and eventually gets out of control; a single ion will then set off a discharge involving many millions of ions.

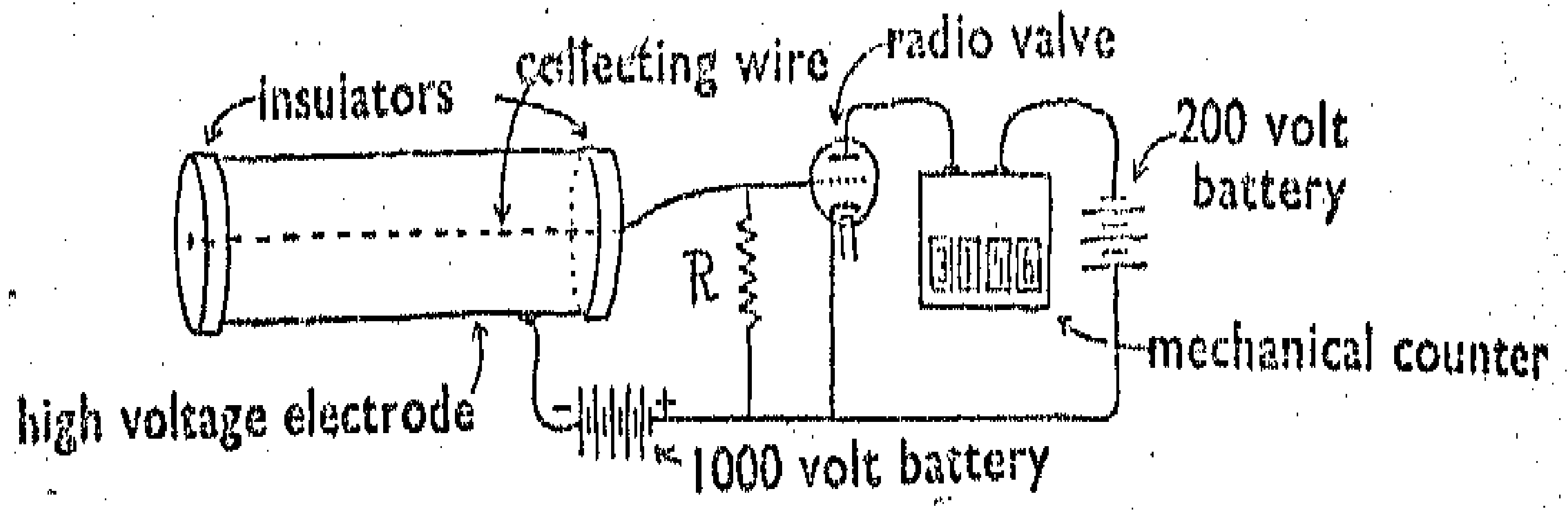

Fig. 21. G-M counter and recording circuit

The Geiger-Müller Counter (or G-M Counter)

Geiger and Müller (Germany) were the first to show how one could quench the discharge so that a fraction of a second later the counter is back in its original condition and ready for the next particle. Each discharge is vigorous enough to be detected by an electroscope, and some of the first investigations with this counter were indeed done by visual observation; however, this method is very tedious and later a simple amplifier was used to operate a mechanical counting device.

The quenching of the discharge can be achieved by making the resistance R (see Fig. 21) very large, a thousand megohms or more, by filling the counter with a special gas mixture (for instance argon containing some alcohol vapour) or by having the amplifier reduce the voltage on the counter for a short time after each pulse. The first method is now little used because the counter takes too long to recover after each pulse; the other two methods both have their champions.

Since an ionizing particle produces all its ions practically at the same time (within a hundred-millionth of a second or less) each particle passing through a G-M counter will produce just one pulse, whether it ionizes only one gas molecule or many thousands, whether the particle is an electron or an alpha particle. However the main value of the G-M counter lies in its ability to count individual electrons. A large number of radioactive isotopes decay under emission of (positive or negative) electrons, and G-M counters are widely used to study this decay or to measure the amount of a certain isotope contained in a given sample. The use of radioactive tracers in chemistry, biology and medicine (see the article on Radioactive Tracers) has brought the G-M counter to numerous laboratories where no nuclear physicist has ever set foot.

Common to all counting methods are three limitations which can be labelled briefly by the words: statistics, background, and resolution.

Nuclear events happen at random, independently of one another. Therefore, the number of events in a given time interval is subject to fluctuations such as are encountered in all statistical phenomena. If 100 pulses are observed in one particular minute this does not mean that the average pulse rate is exactly 100 per minute; it merely indicates that the average is likely to lie between 90 and 110 per minute, although a value even further from 100 is by no means excluded. In general, if N pulses are observed the true average is likely to lie between $N+\sqrt{N}$ and $N-\sqrt{N}$. The uncertainty – $\sqrt{N}$ – grows more slowly than N itself and hence the accuracy improves as more pulses are counted. If the rate at which pulses occur is low one has to run the experiment a long time to accumulate a sufficient number of pulses. At very low rates the time required becomes excessive owing to the presence of the 'background'.

All common materials (glass, metals, etc.) contain traces of radioactive substances, and every counter (or ionization chamber) will therefore occasionally produce pulses all by itself. For each counter this background has to be determined and subtracted from the result of every experiment. This correction becomes relatively large and uncertain if the effect to be measured is very weak.

For instance, if a G-M counter has a background of 30 pulses per minute, the measurement of a sample which produces only one additional pulse per minute is almost impossible. If one works for two hours – one to measure the background, one to measure the sample – one should ideally get $30 \times 60 = 1800$ in the first run and $(30+1) \times 60 = 1860$ counts in the second. Each of these runs is however affected by a statistical uncertainty of about $\sqrt{1800} = 43$; the expected difference of 60 therefore lies at the verge of the statistical uncertainty and its very existence is still doubtful after those two hours' counting. It would take about fifty hours to obtain the strength of the sample with an uncertainty of plus or minus 20 per cent, which is still very inaccurate.

If the problem allows it one will try to arrange for a high counting rate so that the required accuracy can be reached in a short time. This means, however, that the pulses get very close together and occasionally two happen in such quick succession that they are not resolved, and only one is recorded. Mechanical counting devices usually need one hundredth of a second or more to record a pulse, and if another pulse occurs within this time it is not recorded. Hence with increasing counting rate an increasing proportion of pulses is lost, and eventually the mechanical counter jams altogether.

An ingenious device, the 'scale-of-two' (invented by Wynn-Williams) transmits only every second pulse and has a very high resolution since it contains no moving parts, only radio valves. Usually several scales-of-two are arranged in cascade so that each transmits to the next one half of the pulses which it receives. Through this process of repeated halving, the number of pulses with which the mechanical counter has to cope can be greatly reduced; if six scales-of-two are employed in cascade the mechanical counter has to record only every 64th of the original pulses and can therefore easily record many thousands of them per minute. A G-M counter needs about one ten-thousandth of a second to recover after each discharge, and if one does not want to lose more than a few per cent of the particles one should not count more than about ten thousand per minute. With ionization chambers even greater counting rates are feasible.

Scintillation Counters

The earliest counting method of all, after being obsolete for nearly twenty years, has recently staged a dramatic comeback. When an alpha particle falls on zinc sulphide it produces a tiny light flash, just bright enough to be seen in the dark, through a magnifying lens. Visual observation of these 'scintillations' was the only means of counting single alpha particles and protons until about 1925; it was very tiring, slow and unreliable, and was abandoned as soon as electric counting methods were available. Quite recently, photoelectric cells have been improved to the point where they rival the sensitivity of the human eye. As a result, scintillations can now be counted by electronic equipment, automatically, rapidly and reliably. Instead of zinc sulphide, crystals of naphthalene or the chemically related anthracene (or mixtures of the two) are much in use; they give more pulses for a given intensity of gamma rays than a G-M counter, and the pulses are extremely brief (less than a ten-millionth of a second long), allowing very rapid counting and very accurate timing of nuclear events. The use of scintillation counters is spreading rapidly and they will probably supersede G-M counters in many applications. They are sensitive and extremely fast, but stability presents a problem, and the background tends to be high. Also the special photo cells ('photo-multipliers') required are still expensive.

The Photographic Plate

If fast particles fall on a photographic plate they produce (just as light does) a latent image which can be developed. Thus a large number of electrons, either falling on the plate or generated in it through the action of gamma rays, will affect the plate so that, after developing, it appears blackened. It was through this effect that Becquerel discovered radioactivity. The photographic plate is much less sensitive than a counter, but there are experiments where this does not matter and where one wants to know in which place the electrons strike the detecting instrument.

A single alpha particle entering a fine-grained emulsion can make several grains of silver bromide capable of being developed, and hence its trail can be identified later under a strong microscope, as a straight row of about a dozen black dots (silver grains). Thus the photographic plate can be used to make visible the tracks of alpha particles and other fast-moving nuclei.

This way of using photographic plates has gained greatly in popularity during the last few years, following the development of special 'nuclear emulsions' which give much clearer pictures than ordinary plates. Quite recently it has even become possible to record tracks from fast electrons in specially sensitive emulsions. The discovery by C. F. Powell and collaborators of two different kinds of mesons in cosmic radiation was the most striking success of the improved emulsion technique. But also nuclear physics has profited in various ways. Here perhaps the measurement of neutron energies is the most important application. A 'nuclear' plate is exposed for some minutes or hours to neutrons coming from a source which lies in the plane of the plate. Some of the neutrons will collide with and give part of their energy to hydrogen nuclei present in the gelatin. After developing it is possible to pick out those proton tracks which point away from the source and where therefore the proton must have received the full energy of the neutron; this energy can then be found by measuring the length of the track under the microscope. In this way 'neutron spectra' of several groups of neutrons with different speed have been successfully unravelled.

Summary of Detecting Tools

Most of the nuclear research work nowadays is done with counters or ionization chambers; mechanical counting devices are used to record the results. This method combines maximum sensitivity – since it will detect single atomic events – with the capacity – necessary to obtain accurate results – of recording a large number of events in a short time. Isolation of particles of a definite kind is usually possible. By adjusting the amplification, a proportional amplifier can be made to count protons in the presence of electrons, alpha particles in the presence of protons, fission fragments in the presence of alpha particles. On the other hand, a G-M counter will detect electrons while heavier particles are absorbed in its wall, unless it is deliberately made very thin. When the particles are very plentiful they can be measured by an electroscope; this is also a kind of counting method, in the sense that weighing a bag full of coins is equivalent to counting them.

If a phenomenon is new and not yet understood it is often very difficult to unravel it by counting only. This is where the cloud chamber proves of the greatest value, since it shows at a glance the kind of particles involved and their interrelations. Had there been no cloud chamber, the discovery of the neutron, the positron and the meson would no doubt have been made, but later and with much greater effort. On the other hand, the accumulation of a sufficient number of data with a cloud chamber is slow and laborious. The chamber usually has to rest a few minutes after each expansion, and only a few tracks can be photographed each time, or else the picture gets too confused. After the pictures are taken each individual track has to be measured by a human observer. Therefore the cloud chamber is used for actual measurements (as distinct from orientation) only for phenomena which are hard to isolate by counting methods. In some cases the photographic plate can take the place of the cloud chamber; however, measuring the tracks under a high-power microscope is about as laborious as measuring cloud chamber tracks.

ATTACKING TOOLS

In order to provoke a nuclear transformation one has to concentrate a large amount of energy on a nucleus. A rifle bullet has a vastly greater energy than an alpha particle, but its energy is distributed over a very large number of atoms and cannot be made to bear upon a single nucleus.

For this reason the bullets used in transforming nuclei must themselves be of nuclear dimensions. Rutherford discovered the transformation of nitrogen nuclei under the impact of fast helium nuclei (alpha particles) which fortunately are supplied by natural radioactive substances. He realised that the scope of these investigations would be greatly enlarged if other light nuclei could be accelerated artificially to similar or even greater energies. It was under his direction that the first successful experiment of this kind was carried out by J. D. Cockcroft and E. T. S. Walton, the disintegration of lithium by fast protons.

The velocities which must be given to protons or other nuclei, to enable them to cause nuclear transformations, are measured in thousands of miles per second, vastly more than can be achieved by any known mechanical means, including explosives. The only way in which we can impart to them such large velocities is through the action of electric fields on their electric charge. The kinetic energy which a particle acquires on being accelerated is equal to the product of the charge and the electric potential difference between the points between which the acceleration takes place. It is therefore usual to express the energies of particles in units of one electron-volt (abbreviated ev) which is the energy of an electron (or a proton, since it carries the same amount of charge) which has been accelerated by a potential difference of one volt. For the purposes of nuclear physics this is a very small unit and a million ev – written one Mev – is a more appropriate unit. A proton with kinetic energy of 1 Mev has a velocity of about 9000 miles per second.

Only the lightest nuclei are suitable as bullets because heavier nuclei have a larger electric charge and are therefore more strongly repelled by the nuclei which we may want to hit. Most of the work has been done with protons (ordinary hydrogen nuclei), deuterons (nuclei of heavy hydrogen, the rare isotope with atomic weight 2, also called deuterium), and alpha particles (helium nuclei). In the description which follows of various methods of accelerating particles I shall speak of protons by way of example.

High-Voltage Acceleration

The straightforward way of producing protons with energies of, say, 1 Mev is to supply protons at one end of an evacuated tube the ends of which are kept at a potential difference of one million volts. The electric field drives the protons along the tube with increasing speed until, at the other end, they hit the 'target', a layer of the element the atoms of which we want to transform, or of one of its compounds.

The complete arrangement therefore consists of these four main parts: the ion source, where hydrogen is ionized in order to get protons; the acceleration tube in which the protons gather speed; the target where a few of them strike the nuclei which we want to study; and the high-voltage generator from which they derive their energy.

The ion source is built somewhat on the same lines as a radio valve. A hot filament emits electrons, which are drawn towards an anode by a potential of a few hundred volts. A slow stream of hydrogen gas is admitted so that some of the electrons on their way to the anode strike hydrogen molecules and ionize them. The ion source communicates with the accelerating tube through a small opening (say 1/8 of an inch diameter), and those ions which come close to this opening are sucked through by the strong electric field at the other side. If deuterons or helium nuclei are wanted, rather than protons, deuterium or helium is admitted instead of hydrogen.

The accelerating tube is usually made of a number of insulating sections (of glass or porcelain), separated by metal sections which are connected to the high-voltage generator in such a way that the electric potential increases in equal steps from one section to the next. In this way each of the insulating sections has to carry only a fraction of the total potential, and experience shows that it is thereby possible to make the accelerating tube withstand much higher potentials than if it were just one long insulating tube. Several fast pumps (oil diffusion pumps) are attached to the tube to provide a good vacuum, constantly removing the small amounts of hydrogen which leak in from the ion source, along with the ions. A good vacuum is needed to prevent the protons from losing energy by collisions with gas molecules on their way along the tube; furthermore, if the vacuum gets poor, the gas in the tube becomes conducting and the generator is then no longer able to keep up the high electric potential required.

The target has to be cooled since the protons are brought to rest within it and their kinetic energy is converted into heat. Hence the target is often a hollow plate of copper through which water is circulated, covered with a layer of the element which we wish to bombard with protons. Only a thin layer is needed since even fairly fast protons cannot penetrate more than a millimetre of solid matter. The physicist speaks of a 'thick target' if the layer is thick enough to stop the bombarding particles completely. In this case the protons lose their energy gradually on going through the material and may cause disintegrations at any time during this slowing down. If the experimenter wants to study

the effect of protons of well-defined energy he uses a 'thin target', by placing only a trace of the substance wanted onto the target plate, usually by distilling it on in a vacuum. In this thin layer the protons suffer very little loss of energy and the material below is chosen so that they do not cause nuclear transformations in it.

The most difficult task is the production of the necessary high voltage. If the potential difference between two pieces of metal is raised one comes eventually to a point where the insulation of the air between them breaks down; a spark jumps from one piece to the other and the potential abruptly drops to a much lower value. In order to get higher voltages, one has to increase the distance between the two metal pieces; however, at one million volts a spark can traverse a distance of many feet. The resistance of air against electric breakdown can be enhanced several times by increasing its pressure and also by adding small amounts of certain other gases, in particular Freon (dichloro-difluoro-methane, commercially used in refrigeration plants).

Two types of high-voltage generators are at present in most common use: the transformer-rectifier set and the electrostatic belt generator (invented by Van de Graaff and usually called after him).

The transformer-rectifier set is a straightforward application of electrical engineering practice. Alternating current (as supplied by the power company) is converted, by means of a transformer, into a smaller current at higher voltage and is then passed through a rectifier valve (kenotron) which allows it to pass in one direction only. The current which has gone through the rectifier is a pulsating current and is smoothed with the help of large condensers. Every AC-operated radio receiver contains a similar unit for producing a DC-voltage of a few hundred volts, and the main difference lies in the necessity of using larger transformers, rectifiers, and condensers in order to get higher voltages. Since the transformer is the most expensive part and its price rises rapidly with its peak voltage, considerable ingenuity has been employed in the successful design of systems where the output voltage is several times larger than the peak voltage of the transformer used.

The 'Van de Graaff' is a brilliant offspring of the ancient family of electrostatic machines, once the glory of the physicist's art, now mostly relegated to a dusty corner of the lecture room. The fundamental principle of these machines is that electric charges can be carried bodily from one point to another by means of rotating discs, made of an insulating material. In the Van de Graaff the disc is replaced by an insulating belt travelling around two pulleys. Charge is sprayed onto the belt near one pulley and taken off to a large hollow metal sphere which surrounds the other pulley. As more and more charge accumulates on the metal sphere the potential rises until either a spark occurs or enough current leaks off the sphere to prevent the voltage from rising any further. For attaining voltages above a million volts, the whole arrangement (including the accelerating tube and ion source) is placed inside a large steel tank into which air (containing some freon) is pumped to a pressure of about 100 pounds per square inch. The target is usually placed at the end of a tube, several feet long, which protrudes from the steel tank in order to make the target easily accessible to whatever detecting tools are to be used. The belt and accelerating tube may be horizontal (Fig. 22) or vertical (plate 17).

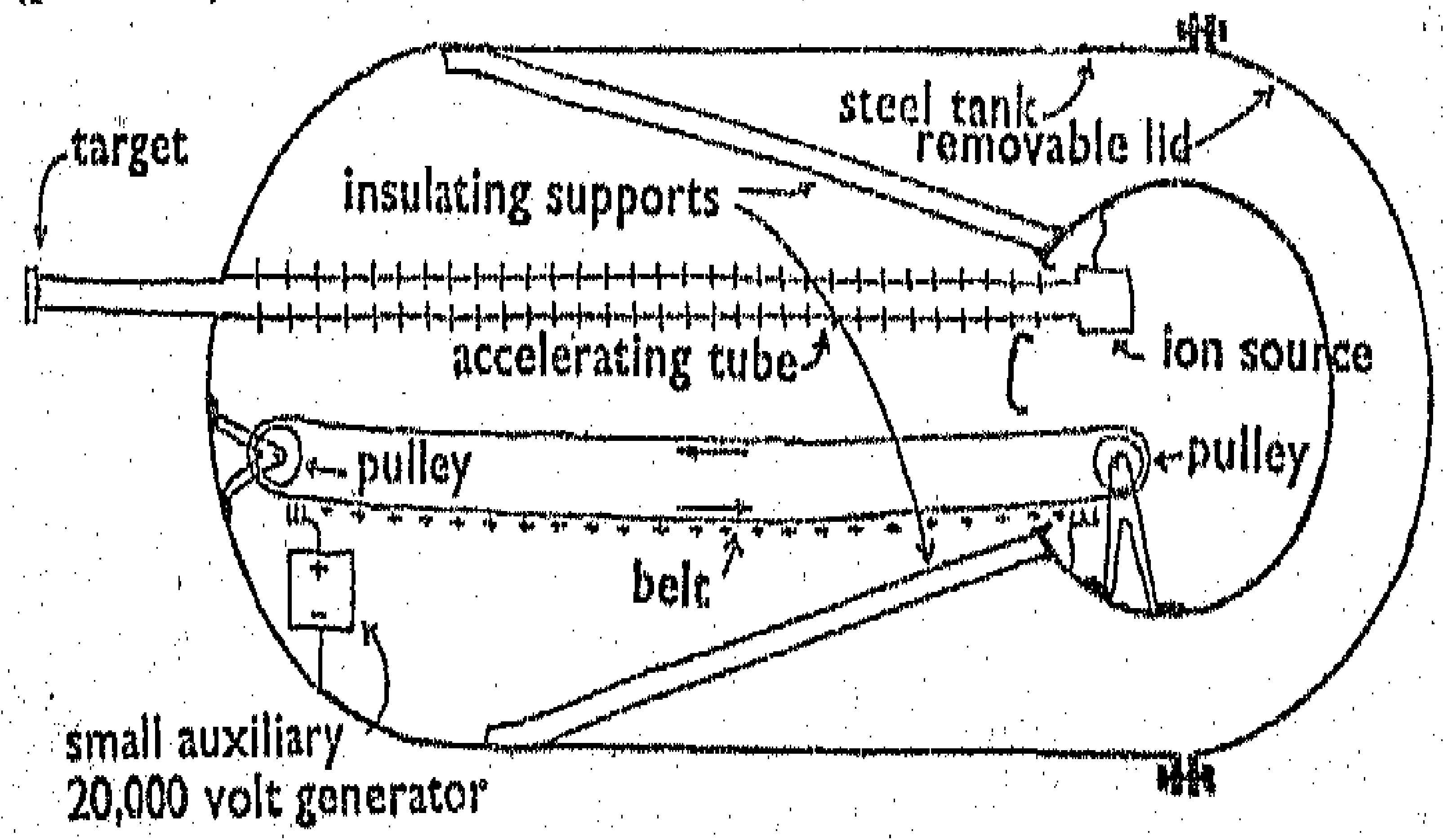

Fig. 22. Belt generator (Van de Graaff), with accelerating tube, schematical.

Transformer-kenotron sets have been built for voltages up to about two million volts, and with belt generators about four million volts have been reached. Further slow progress along these lines is likely. In the meantime, several methods were discovered whereby it is possible to impart energies of many Mev to particles without actually generating such high voltages.

Multiple Acceleration; the Cyclotron

The first attempt of this kind was the linear multiple accelerator. A number of short metal tubes are lined up inside an evacuated container, with an ion source at one end; all the even tubes are connected together, and so are all the odd ones. If we were to place a constant potential difference between the two groups of tubes, for instance making the odd ones positive with respect to the even ones, a proton would be accelerated on passing from the first to the second tube, but would lose this extra energy again on passing from the second to the third tube. We can however use the time which the proton spends in the second tube to reverse the potential difference between the two tube systems so that the proton gets accelerated again as it enters the third tube, and this reversing process can be repeated for every tube in the system, so that the protons emerge with an energy which corresponds to the potential difference used multiplied by the number of tubes. To produce the required voltage reversals, the odd and even tubes are connected to a high-frequency generator (similar to a radio transmitter). The tubes are made longer and longer with increasing distance from the ion source, so that the ions spend the same time in each tube, despite their increasing velocity.

In order to get worth-while energies one has to have a large number of tubes, and then the apparatus becomes impracticably long (hundreds of feet). The idea which made the method practicable was to put everything into a strong magnetic field, because in such a field the path of a freely moving charged particle is a circle rather than a straight line. And here one very fortunate fact is of decisive importance: As the particle gets faster the circle on which it moves increases in size in just such a way that the time needed for a full revolution remains the same.

The instrument which was based on this idea soon became known under the name 'cyclotron'. Instead of a number of tubes, only two accelerating electrodes are needed which are called dees, for their similarity in shape with a capital 'D'. Together they form a hollow metallic 'pill box', cut along one diameter. They are placed in an evacuated container, between the pole pieces of a very large electromagnet designed to produce a strong uniform magnetic field across them (see Fig. 23). Ions are produced near the centre of the dees, with the help of an ion source somewhat similar to the one described earlier. Those ions which emerge from the source at the right time will be accelerated into one of the dees; after describing a semicircle within it, the ion will get to the edge of the dee when the voltage (delivered to the dees from a high-frequency generator) has changed direction so that the ions get accelerated again. Of course the frequency of the field has to be carefully adjusted so that the ions keep in step with it. If this adjustment is achieved (largely by trial and error) each ion will move on an expanding spiral, gaining energy every time it crosses the gap between the two dees, until it hits the edge of one dee. If one wants to utilise as many of the fast ions as possible one uses an 'internal target' which intercepts the ions before they reach the edge of the dee; alternatively, it is possible to deflect part of the ions by means of strong electric fields and to guide them to a point outside the magnetic field where the target is more easily accessible.

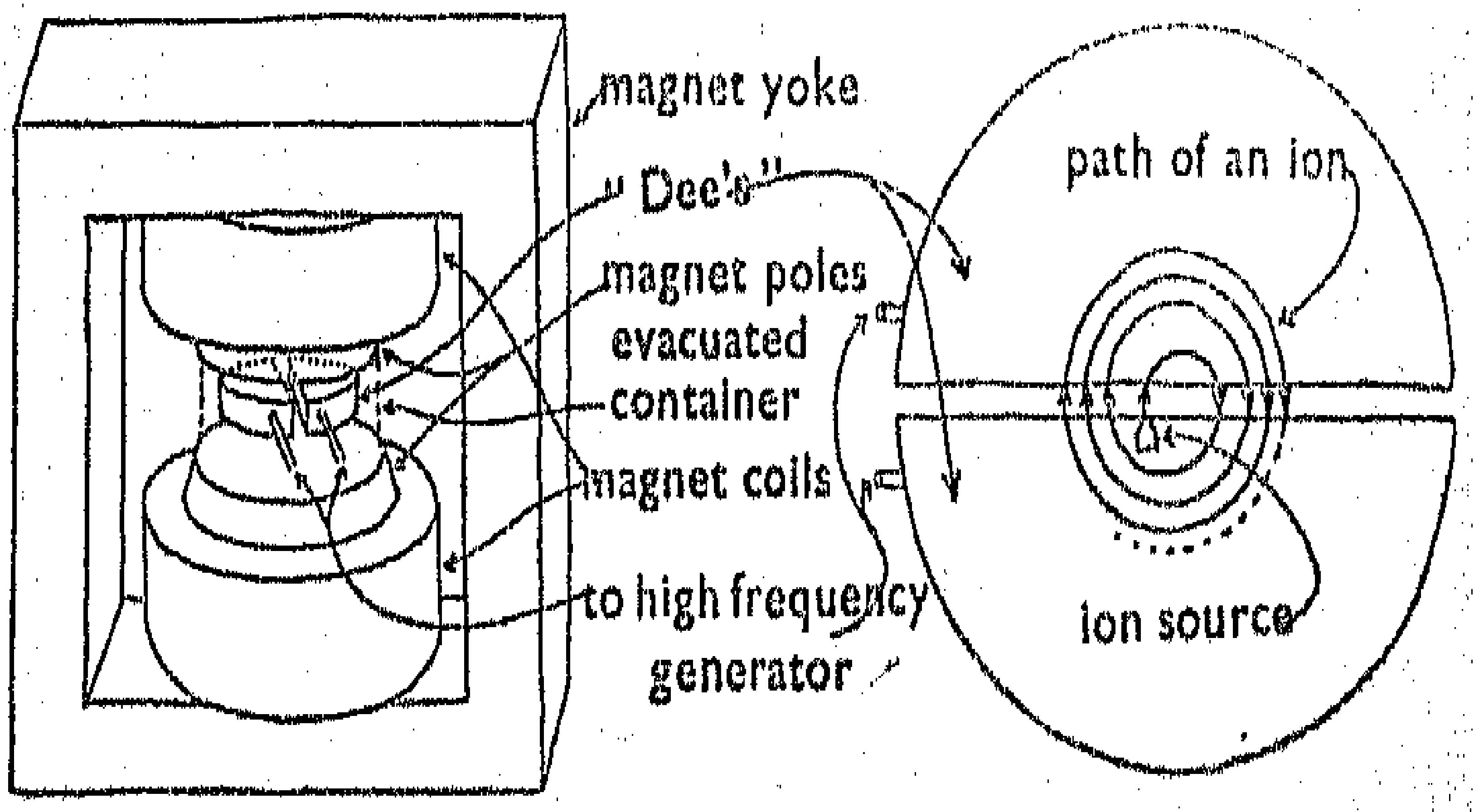

Fig 23. Cyclotron, schematical.

By enlarging the magnet and the dees one can enable the ions to spiral out further and thus to gather more energy. For this reason, cyclotrons of ever-increasing size have been built in order to get particles of ever greater energies. The largest cyclotron at present has a magnet which weighs 3000 tons, with pole pieces 15 feet in diameter. It was built in Berkeley, California, by E. O. Lawrence (the inventor of the cyclotron) and his team. It produces deuterons of 200 Mev, and other particles with even greater energies. In this machine it is no longer strictly correct that an ion always needs the same time for a full revolution in a given magnetic field independent of its speed. According to relativity theory the weight of a body increases when its speed ceases to be very small compared to that of light. A deuteron of 200 Mev has a mass which is 10 per cent greater than normal, and the time it takes for one revolution in a magnetic field has also increased by 10 per cent.

In order to allow for this slower circulation the large Berkeley cyclotron is operated with 'frequency modulation'. That is, the frequency of the electric potential applied to the dees is made to vary periodically by some 10 per cent. Those ions which happen to start when the frequency is highest can get accelerated all the way out; the drop of frequency during the next thousandth of a second or so while they are being accelerated takes account of their increasing mass. The acceleration therefore depends on artificially establishing synchronism between the driving field and the motion of the particles, and this type of machine is often called a synchro-cyclotron. The first of its kind in Great Britain started work in Harwell a few months ago.

Machines for accelerating nuclear particles to even higher energies are being built in various places. Oliphant, in Birmingham, is well under way with a machine designed to produce protons of over 1000 Mev, based on a principle somewhat different from that of the cyclotron. Machines for even larger energies, in which the particle describes a kind of huge rectangle with rounded corners (the rounding produced by magnets) are being built in the U.S.A. The estimated cost of one of these machines is about two million pounds.

Somewhat different methods are being used to accelerate electrons to very high energies. The multiple linear accelerator has staged a come-back, helped by the great progress that has been made, thanks to radar, in the techniques of producing short electric waves of great intensity. Another instrument is the betatron, with which electrons of over 100 Mev have been produced.

The Induction Accelerator ('Betatron')

The betatron is an ingenious application of the principles on which the operation of a transformer depends. In a transformer, an alternating electric current is sent through a coil (the 'primary') which surrounds an iron core. The oscillations in the magnetism of the core, caused by the oscillating primary current, produce an oscillating voltage in the 'secondary' coil which also surrounds the iron core. This voltage is proportional to the number of turns in the secondary coil, and it is not difficult to build a transformer which will produce 100 volts per turn. A secondary coil containing a million turns would theoretically produce a voltage of one hundred million volts, but of course the insulation would break down long before such a voltage was reached.

In the betatron there is no secondary coil. Instead, there is a circular tube of glass or porcelain (shaped like the inner tube of a tyre) in which electrons are made to go round a large number of times. For each circuit the electron gains an amount of energy corresponding to the voltage produced in a single turn of an imaginary secondary coil, or about 100 volts, and it is actually possible to make the electrons go round approximately a million times. A portion of the magnetic field is diverted from the iron core to where the electrons are circulating, in order to bend their path to a circle of the desired size. The first successful betatron was built in the U.S.A. during the war (by D. W. Kerst, in about 1941). Late in 1945 the General Electric Company, Schenectady, announced the successful operation of a betatron for making electrons of 100 Mev. For much higher energies the betatron becomes inefficient, and the acceleration of the electrons has to be aided by a high frequency field as in the cyclotron. This hybrid is called a synchrotron. It was first proposed by Veksler (U.S.S.R.), but the first small synchrotron was made to work in this country about two years ago. One built by E. M. McMillan in Berkeley started operation at 330 Mev in 1949, and several of similar size (including one in Glasgow) are nearing completion.

Neutron Production

Neutrons do not occur in nature (except in very small numbers in the cosmic radiation) and if they did we could not accelerate them since they carry no electric charge. If we want neutrons we have to produce, with the help of protons or other charged particles, some nuclear transformations in which neutrons are liberated.

One way to do this is to bombard beryllium with alpha particles from a radioactive source. For instance, some radium salt is mixed with an excess of beryllium (both finely powdered) and enclosed in an airtight capsule (perhaps half an inch overall size). Such a source will emit the order of a million neutrons per second uniformly in all directions; it is easily fitted into any experimental setup, and practically unchanged with time. Nearly all the fundamental properties of neutrons were discovered with sources of this type.

The neutrons emitted from a radium-beryllium source are very heterogeneous, with kinetic energies varying between 0.1 and 10 Mev, approximately. By using artificially accelerated particles it is possible to produce homogeneous neutrons, that is, neutrons which have all very nearly the same energy. For instance, by bombarding deuterium with deuterons of 0.1 or 0.2 Mev (only a small transformer-kenotron set is needed) one gets neutrons of 2.5 Mev energy. A thin target of lithium, bombarded with protons of about 2 to 3 Mev (from a Van de Graaff) serves as a source of neutrons with energies which can be varied between almost zero and about 1 Mev, simply by varying the voltage of the Van de Graaff. Very fast neutrons, and enormous numbers of them, are obtained by bombarding lithium with fast deuterons from a cyclotron.

The most powerful neutron source of all has recently come into existence through the realisation of nuclear chain reactions. The number of neutrons produced by a large graphite pile running at full power is millions of times greater than what can be obtained from a cyclotron. The Harwell pile which began to operate in August 1948 produces more than 10^{17} neutrons every second and has facilities for pursuing a number of researches at the same time. (See the article on Nuclear Reactors.)

Since neutrons are electrically neutral they are not repelled by the electric charge of atomic nuclei, and therefore can approach them even if they are quite slow. Some nuclei are even much more strongly affected by slow neutrons than by fast ones. Neutrons can be slowed down very easily by moderators like water or paraffin wax which contain much hydrogen. Each time a neutron collides with a hydrogen nucleus it loses, on an average, half its energy. After some twenty collisions its energy has become so low that it is comparable to the energy which the hydrogen atoms themselves have, on account of their heat motion (thermal agitation). After that, the neutron is just as likely to gain as to lose energy on colliding with a nucleus and it continues to wander aimlessly around in the material as a 'thermal neutron' until it eventually combines with one of the nuclei present, or else escapes from the material. Graphite is an even better moderator; a neutron loses less energy per collision, but has also much less chance of being captured than in water.

AUXILIARY TECHNIQUES

In addition to attacking tools – to cause nuclear transformations – and detecting tools – to detect the particles which result from those transformations – the nuclear physicist needs a number of techniques which serve to separate, out of a multitude of things which happen all at once, the particular phenomenon which he wants to observe. Out of the large variety of such techniques, I shall describe a few of the more important ones.

Collimation

Alpha particles are very easy to collimate, that is, to confine into a narrow beam; two small apertures cut into thin metal sheet or even paper will do the trick, one aperture being placed close to the source of particles, the other a little distance away. With electrons, the sheet has to be thicker, and furthermore, electrons tend to get deflected by collisions with air molecules, hence for good collimation the electron source and the collimating apertures have to be put into an evacuated container. Gamma rays can penetrate inches of solid lead; to collimate them, the source must be placed at the centre of a large lead block (say, a cube with sides a foot long) with a hole drilled from the surface to the centre. Neutrons can be collimated like gamma rays, only paraffin wax is used instead of lead, and an even greater thickness of material is needed (about two feet).

In many cases collimation can be achieved without the use of collimating apertures, simply by placing the detector at such a distance from the source that only particles within a narrow range of directions can hit the detector at all.

Absorbers

Alpha particles are completely stopped by a piece of paper. Mica can be split to produce sheets which are much thinner than paper and very uniform; the thickness of such a sheet can be found by weighing. If increasing thicknesses of mica are placed in a collimated beam of alpha particles of uniform energy the number which emerge remains unchanged at first, but drops to zero quite rapidly if the thickness of mica exceeds a certain amount; by measuring this amount one can find the energy of the alpha particles. If the alpha particles are a mixture of particles with two different energies, the number recorded will drop to zero in two steps as the thickness of mica is increased.

Electrons behave somewhat similarly, only the drop to zero is much more gradual. As a result, the use of absorbers (in this case usually thin sheets of aluminium) allows one to determine the greatest energy represented among the electrons in question, but gives only very vague indications concerning the presence of electrons of lower energy. The energy of electrons is most accurately measured by observing the curvature of their path in a strong magnetic field, either by the use of the cloud chamber, or by special devices (electron spectrometers, see plate 15).

In the case of gamma rays – and even more so of neutrons – the use of absorbers is generally not the best way for energy determination. Neutron energies are usually measured with photographic plates (see above); gamma ray energies can be obtained quite accurately by measuring the energy of electrons knocked out from a foil, using a cloud chamber or an electron spectrograph.

The Coincidence Method

If an electron passes through two G-M counters it will produce a discharge in each, and the two discharges will be practically simultaneous. One can connect the two counters to a valve circuit which is made so that it will operate a mechanical counter if, and only if, both G-M counters discharge at the same time. Such a circuit is called a coincidence circuit.

One interesting application of a coincidence circuit is the following method for the determination of the energy of gamma rays. The gamma rays are allowed to fall on a thin metal foil; most of the gamma quanta go through but some of them eject electrons from the foil. If one now tries to determine the maximum energy of these electrons (which is equal to the energy of the gamma quanta) by measuring their absorption in metal foils, as mentioned before, the absorption effect will be partly masked by the fact that, as we increase the thickness of the absorber, additional electrons are ejected from the absorber by the gamma rays. However if the original electrons are recorded by two G-M counters connected to a coincidence circuit, and the absorber foils are placed between the two counters, then the additional electrons will pass only through one of the two counters and will therefore not be recorded, and the absorption of the electrons ejected from the first metal foil can be determined correctly.

Another application of coincidence circuits is the investigation of nuclear reactions which result in the simultaneous emission of two particles from the same nucleus. It is also possible to connect more than two, that is, three, four or more G-M counters to the same coincidence circuit and thus to select, for instance, electrons, travelling in a given direction, which have been emitted simultaneously with two gamma quanta, without being disturbed by the presence of numerous other electrons and gamma quanta which do not fulfil this special condition. It is easily seen that the coincidence method is indeed a very powerful and versatile tool for disentangling nuclear phenomena, in particular when the new scintillation counters (see above) are employed.

Neutron Detection

Fast neutrons are detected usually by their capacity to collide with hydrogen nuclei and to transfer part of their energy to them; the fast protons which result can be detected with an ionization chamber connected to an amplifier. For this purpose, the ionization chamber is either filled with hydrogen or lined with a thin layer of a hydrogenous compound such as paraffin wax. Slow neutrons, in particular thermal ones, have too little energy to be detected in this way. Here one can make use of the fact that boron nuclei are very readily transformed by slow neutrons, under emission of fast alpha particles which are easily detected. The 'boron chamber', an ionization chamber lined with boron or else filled with gaseous boron trifluoride, is a very convenient and widely used instrument for measuring the intensity of a stream of slow neutrons.

An entirely different method depends on the fact that certain elements (gold, iodine, manganese and many others) become radioactive under the action of slow neutrons. This activity can be measured with a G-M counter or, if it is strong enough, with an electroscope.

Radioactivity: Decay Curves

Many nuclear reactions result in the formation of a nucleus which is unstable and tends to disintegrate spontaneously after some time, in most cases with the emission of a (positive or negative) electron. For instance, if sodium is exposed to slow neutrons some of the neutrons are captured by sodium nuclei, resulting in the production of sodium with the atomic weight 24 (ordinary sodium has 23). If a sample of this irradiated sodium is placed near a G-M counter one finds that the counting rate due to the sample decreases with time in a quite defined fashion. If the rate decreases by a certain factor during the first hour it will decrease by the same factor during the second hour, or indeed during any hour, and the same statement is true if, instead of one hour, some other time interval is chosen. It is usual to characterise the rate at which a given radioactive substance decays by indicating the so-called half-life, that is, the time interval in which the counting rate drops to one half. The half-life of sodium 24 is 15.5 hours; hence in $2\times 15.5=31$ hours the counting rate drops by a factor 4, in $3\times 15.5=46.5$ hours by a factor 8, and so on.

At this point it is convenient to consider the logarithm of the counting rate. If a number decreases by a certain *factor* its logarithm decreases by a certain *amount*. Hence the logarithm of the counting rate, in our example, decreases by a constant amount every hour. If we make a graphical representation of the logarithm of the counting rate as a function of time (just as a business manager represents the varying rate of sales by a curve) we get a curve which descends with a constant slope; in other words, a straight line.

From the slope of this line, the half-life can be obtained at a glance, and the fact that the line is indeed straight assures the experimenter that he is dealing with a pure radioactive sample. If his sample contains a mixture of two or more active isotopes the line will no longer be straight. For instance, if sodium is irradiated with fast, rather than slow, neutrons the activity of the sample is found to drop very rapidly for the first minute or so, then more slowly during the next half hour, and finally at a slow rate corresponding again to a half-life of 15.5 hours. If the logarithm of the counting rate is plotted against time as before one obtains a curved line (Fig. 24). This line can be shown to be a 'superposition' of three straight lines; in other words, the sample contains a mixture of three active isotopes, the half-lives of which turn out to be 40 seconds, 10 minutes and 15.5 hours. If more than three or four radioactive isotopes are present in a sample, and in particular if their half-lives are not widely different (as they fortunately are in the case of sodium) this analysis of the decay curve becomes very unreliable, and the chemist must be called in to help.

Chemical Separation

In most cases the radioactive substances which result from the bombardment of a certain element are not all isotopes of the same element and can therefore be separated by chemical methods. One may for instance dissolve the sample and then add some reagent which will precipitate one of the elements in question but not the others. One peculiar difficulty lies in the fact that although the reagent may form an insoluble compound with the element which we want to separate, so little of it is usually created in the nuclear transformation that no solid grains can be formed which are big enough to be held back on a filter, and hence no precipitate is formed which can be filtered off. One therefore usually adds to the solution a small amount of the element which one is trying to separate, so that a precipitate may be formed. This so-called carrier is ordinary, non-radioactive material and therefore does not disturb the radioactive measurements.

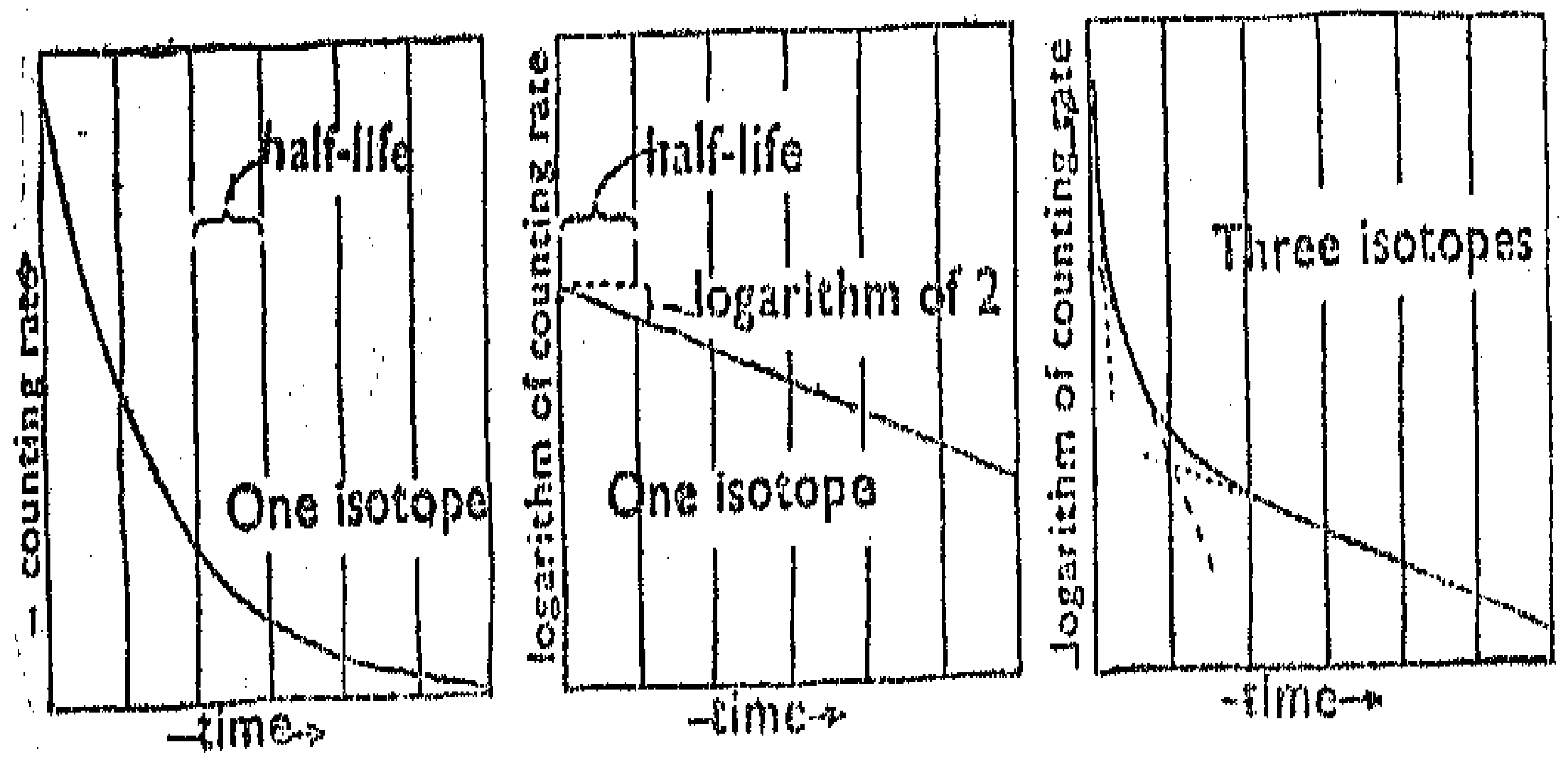

Fig 24. Decay curves

The transformation of uranium by neutrons, which forms the basis of atomic power, is such a complex superposition of different processes that for about three years it frustrated the efforts of scientists in Rome, Paris and Berlin. Clues to the right answer accumulated but were not recognised. Following one of these clues, Hahn and Strassmann in Berlin fixed their attention on a certain active substance which resulted from the bombardment of uranium with neutrons, and which could be precipitated with barium as a carrier. This fact did not yet prove that the substance in question was an isotope of barium, for radium behaves similarly. The crucial experiment was the attempt to separate the unknown substance from its barium carrier, an attempt which was unsuccessful, while a small amount of a known radium isotope which had deliberately been added was readily separated from the barium carrier. This experiment proved conclusively that the unknown active product was an isotope not of radium but of barium. Since the barium nucleus has less than two-thirds of the charge of the uranium nucleus, the conclusion that the uranium nucleus, on impact of a neutron, may break into two pieces of comparable size had become unavoidable and was indeed soon confirmed by physical experiments. It was soon found that it is not so that one of the fragments is always a barium nucleus; the uranium nucleus can break in a variety of ways, and isotopes of more than twenty elements have been found among the products of nuclear fission.

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About the Contributors

W. J. ARROL graduated at London University in 1935 and in the same year started to do research involving the measurement of small quantities of radioactive substances. During the early part of the war, he spent three years in the Navy as a Radar officer and then joined the Anglo-Canadian atomic energy project in 1943. Returning to England in 1945, he became a lecturer and senior lecturer at London University, but left to join the Atomic Energy Research Establishment at Harwell in 1948. He is now in charge of the Chemical Separation Group of the Isotopes Division at Harwell.

HANS A. BETHE was born in Strasbourg in 1906, and educated at Frankfurt and Munich Universities, receiving his Ph.D. in Physics in the latter in 1928. Held various positions in German universities from 1928 to 1933, when he came to England, to the Universities of Manchester and Bristol. Since 1935 he has been Professor of Physics at Cornell University, Ithaca, New York, while from 1943 to 1946 he was Chief of Theoretical Physics Division, Los Alamos Atomic Bomb Laboratory. His main work is on the quantum theory and the theory of the atomic nucleus, and his publications are to be found in various scientific journals, especially the *Proceedings of the Royal Society* and the *Physical Review.*

SIR JOHN COCKCROFT, C.B.E., F.R.S., has been Director of the Atomic Energy Research Establishment at Harwell in Berkshire since 1946. He was educated at Todmorden Secondary School and Manchester University; and then worked under Rutherford at the Cavendish Laboratory, Cambridge, becoming in time a Fellow of St John's College, and Jacksonian Professor of Natural Philosophy. During World War II he became Chief Superintendent of the Air Defence Research and Development Establishment, and then in 1944 Director of the Canadian Atomic Energy Division. In 1950 he received the cross Chevalier of the Legion of Honour.

J. L. CRAMMER is editor of *Science News* and a doctor, and until recently was a Squadron Leader in the R.A.F. Medical Service. He was educated at Cambridge and University College Hospital and specialised in biochemistry.

K. FEARNSIDE was born in 1919 and educated at St John's College, Cambridge, where as an Open Major Scholar he studied under Sir John Cockcroft. He graduated in Physics with first-class honours in 1940 and joined the Royal Air Force as a Radar Officer. After spending six years on active service overseas, he joined the staff of the Atomic Energy Research Establishment in October 1946 and was until March 1950 in charge of the Isotope Physics Group there. He is now Technical Director of Isotope Developments, Ltd.

OTTO ROBERT FRISCH, O.B.E., F.R.S., was born in Vienna in 1904, and studied at that University till he received his Ph.D. in 1926. He has been occupied in research at Berlin (1927–30), Hamburg (1930–3), London (1933–4) and Copenhagen (1934–9). In 1940 he joined the atomic bomb project in Liverpool and later went to the bomb research establishment at Los Alamos to continue this work (1943–6). He is the co-author (with Professor Lise Meitner) of the paper in which the term 'nuclear fission' occurs for the first time, and the first to demonstrate experimentally the enormous energy liberated by the fission of a uranium nucleus. In 1947 he was appointed Jacksonian Professor of Natural Philosophy at Cambridge University, Head of the Nuclear Physics Section at the Cavendish Laboratory, and in 1948, Fellow of Trinity College.

PHILIP MORRISON is Associate Professor of Physics at Cornell University, and was closely concerned with the atomic bomb project. He was a physicist at the Metallurgical Laboratory at the University of Chicago, and then at the Los Alamos Laboratory in New Mexico; a member of the group which carried out the test shot of the bomb; and in July 1945 was in Japan with the group which investigated the damage of the atomic bombs and examined the position of atomic research in Japan. Professor Morrison received his B.S. degree from the Carnegie Institute of Technology and his Ph.D. degree from the University of California in 1940. Before the war he was connected with the physics department of the University of Illinois, and has been on the faculty of Cornell University since 1946.

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